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DEBARKING CHIPPED LOGGING RESIDUES:

TECHNIQUE AND POTENTIAL IMPACT

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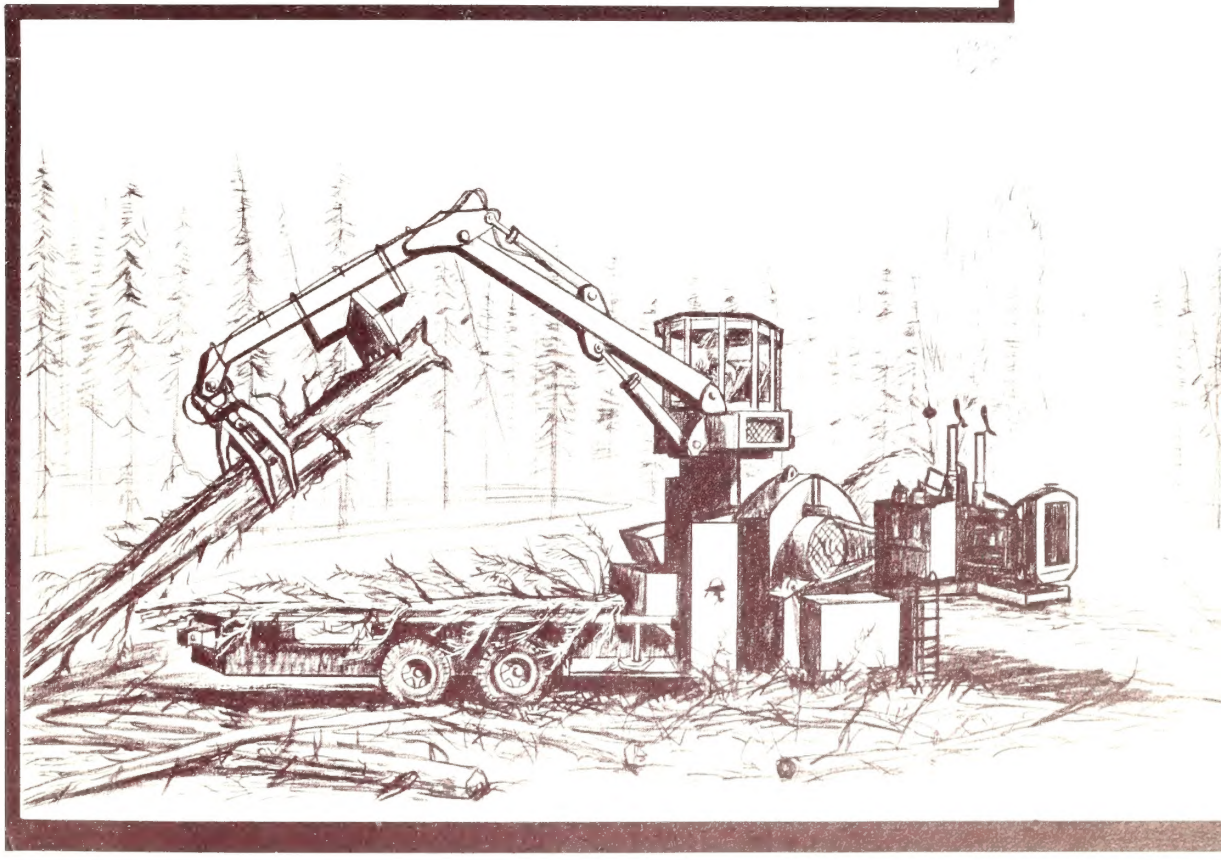
Rodger A. Arola
and John Host



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INTERMOUNTAIN FOREST AND RANGE
EXPERIMENT STATION

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DEBARKING CHIPPED LOGGING RESIDUES:

TECHNIQUE AND POTENTIAL IMPACT

Rodger A. Arola and John Host

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ABSTRACT

Woods-run samples of four Intermountain species (western larch, Douglas-fir, ponderosa pine, and lodgepole pine) were chipped separately, then processed through the chip debarking system developed by the Forest Service's Forest Engineering Laboratory at Houghton, Michigan. When the chips retained for each species were mixed together, bark content ranged from 1 percent for lodgepole pine to 7 percent for western larch. Bark removal ranged from 60 to 85 percent, wood loss from 8 to 13 percent.

INTRODUCTION

One of the most promising approaches to intensive utilization of logging residues is to chip cull trees and logging slash in the woods by means of small, mobile chippers, then transport the chips to manufacturing plants that utilize wood fiber. In a recent study in Wyoming (Benson 1974), this system increased by 35 percent the wood fiber that would have been recovered by conventional logging alone.

Despite the advances in chipping and residue handling equipment, the chipping of forest residues on a large scale in the Intermountain West has not generated much interest. One of the main reasons is that current models of mobile chippers produce barky chips that do not meet industry specifications for many products. Barky chips face low demand at prices that do not cover the costs of chipping and transportation. Until a method for debarking the chips is devised, intensive utilization of waste wood in the Intermountain area will remain economically unattractive.

The Forest Engineering Laboratory, Houghton, Michigan, has recently developed a system that will remove bark from chipped residues (Arola and Hillstrom 1972; Arola and Erickson 1973; Hillstrom 1973). The system has recently been applied to chipped whole trees and logging residues from Intermountain species--Douglas-fir, western larch, ponderosa pine, and lodgepole pine. This report presents the results of the study and projects the potential impact of implementing chip debarking on a regionwide basis.

Figure 1 shows forest residues in overmature lodgepole pine stands on the Bitterroot National Forest. In many instances, volumes in these stands are divided a third green, a third dead standing, and a third down. Figure 2 shows the same stand after partial logging. The foreground has 960 cubic feet, or 14.4 tons, per acre of residue. Logs in the background have not yet been skidded out. Utilization was down to 2.5-inch top diameter. In contrast, figure 3 shows logging residues of 70 tons per acre, after burning slash in mixed spruce-fir, where utilization was down to 6-inch minimum top diameter.

Figure 1.--Typical residues in overmature lodgepole pine on the Bitterroot National Forest.

Figure 2.--Postlogging residue in overmature lodgepole pine stand.

western Montana.

CHIP DEBARKING SYSTEM

The debarking system consists of presteaming, compression debarking, optional mechanical attrition, with intermediate and final screening (fig. 4). Presteaming conditions the barky chips and improves bark removal during the compression debarking stage. Presteaming improves the bark removal by as much as 100 percent over unsteamed chips, depending on species and time of the year the trees were harvested.

The compression debarker consists of two steel rolls. By adjusting the position of roll stops, a predetermined nip spacing can be set between the rolls. Two hydraulic cylinders hold the adjustment roll in place and control the degree of compression to which the chips are subjected. The surfaces of the two compression rolls can be varied. In the initial tests conducted with the Intermountain species, one smooth and one knurled roll were used.

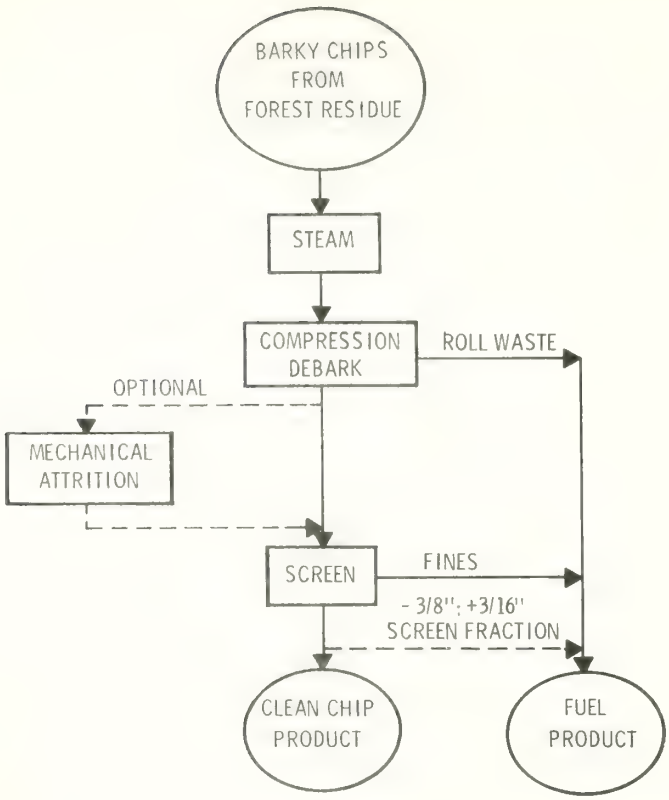


Figure 4.--Flow chart of system for upgrading barky chips produced from forest residue.

Bark removal is caused by bark adhering to the compression rolls where it is scraped off and collected. Additionally, some of the bark is fragmented into fines and removed by screening. The optional mechanical attrition process can be used to break down an additional amount of bark into fines for subsequent removal in the final screening stage.

The chip debarking efficiency is indicated by:

1. Bark content--a percentage of total chip output.

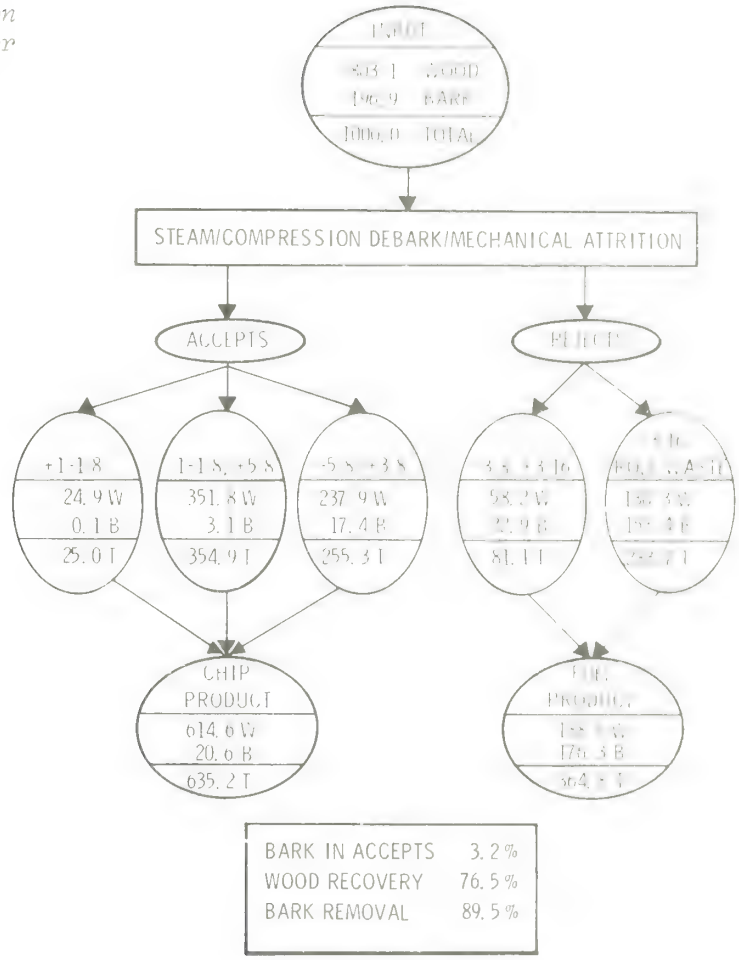
2. Debarking ratio--the ratio of output bark to input bark.

3. Percent wood loss--the amount of wood fiber lost as fines and adherence to the rolls.

Chip screens of 3/16-, 3/8-, and 5/8-inch openings are used to measure chip quality. Fines, material under 3/16 inch in size, can be used for fuel or other uses; chips over 1-1/8 inch are rechipped. Retained chips are used for pulping.

Initial tests with Intermountain residues were done with one smooth roller and one knurled roll. Figure 5 shows the average results based on 1,000 pounds of chipped material. Wood loss for these tests was generally high, much of it being attributed to the knurled roll.

Figure 5.--Material balance based on average chip debarking results for several species of Intermountain logging residue (green material only).



A second test of Intermountain species was undertaken as part of the Wyoming Residue Study (Gardner and Hann 1972). The chips were produced from logging residues, were stored for 1 year, and then were processed through three different levels of chip debarking treatments (table 1). A slight improvement over the previous study was found. Overall, the output bark content for all three treatments was around 2 percent.

Table 1.--*Debarking of lodgepole pine chips from Wyoming Residue Study*

Process code[1]	Input bark	Output bark	Output/input ratio	Wood loss
	Percent			
C	8.1	2.1	0.26	[illegible]
SC	8.9	2.0	.23	[illegible]
SCD	9.8	1.8	.19	21.4

[1] C - compression debarking.
SC - steaming and compression debarking.
SCD - steaming, compression, debarking, and drubbing.

FOLLOWUP TESTS

The promising bark removal results obtained in previous studies prompted a followup study having the goal of reducing wood fiber loss while maintaining or improving the level of bark removal. Because much of the wood loss in the initial study was attributed to the knurled roll on the compression debarker, the followup tests were done with smooth rolls. Roll nip spacing was 0.020 inch. Nip pressure was adjusted to approximately 1,400 pounds per lineal inch.

Green logging residues of the four species chipped in the initial study were used in the followup study. The presence of considerable bark within each size fraction indicated that screening alone would not separate sufficient quantities of bark from wood chips. Therefore, only those chips passing through the 1-1/8 inch screen but retained on the 3/16-inch screen were processed.

The chips were analyzed for bark content within each size fraction after processing (table 2). With all four species, the 5/8-inch screen fraction had less than 1 percent bark and represented about one-third to one-half of the total chip output. The 3/8-inch screen fraction represented close to an additional 40 to 50 percent of the chip output, with a residual bark content ranging between 1 and 6.5 percent. The 3/16-inch screen fraction had the highest residual bark content, ranging between 5 percent and slightly over 20 percent. However, this small screen fraction represented only 10 to 20 percent of the output.

When the retained screen fractions for each species were mixed together, the output bark content was 1 percent for lodgepole pine and 7 percent for western larch. Bark removal ranged from 60 to 85 percent and the wood loss between 8 and 13 percent (table 2).

By rejecting the 3/16-inch screen fraction from the output (because of the high bark content), residual bark in the accept chips (+3/8-inch) was reduced considerably. Douglas-fir, lodgepole pine, and ponderosa pine all contained less than 2.5 percent bark, and western larch 4 percent. Rejecting this fraction doubled wood fiber losses--to a range between 16 and 28 percent.

This wood loss may not be intolerable, when one considers that this system allows for 70 to 85 percent wood fiber recovery at relatively low bark contents from material not being utilized. The rejected fractions can be used as fuel.

A materials balance was made based on 1,000 pounds of lodgepole pine chips containing slightly over 6 percent input bark (fig. 6). Output was classified into two categories--accepts and rejects. The accept chips were those retained on a 3/8-inch or larger screen. The reject material was the roll waste and all material passing a

Table 2.--*Chip debarking results for four Northern Rocky Mountain conifer species*

Species	Process[2] code	Chip screen size: 5/8-inch Retained chips: Wood	5/8-inch Retained chips: Bark	5/8-inch: Wood loss	3/8-inch Retained chips: Wood	3/8-inch Retained chips: Bark	3/8-inch: Wood loss	5/16-inch chips: Wood	5/16-inch chips: Bark
Western larch	SCD	99.2	0.8	72.8	[illegible]	[illegible]	[illegible]	80.4	[illegible]
Western larch	SCD	99.5	.5	72.4	95.4	1.6	25.2	[illegible]	[illegible]
Douglas-fir	SCD	99.5	.5	[illegible]	96.1	[illegible]	23.3	[illegible]	[illegible]
Douglas-fir	SCD	99.7	.3	66.8	95.7	[illegible]	22.3	81.7	[illegible]
Ponderosa pine	SCD	99.7	.3	59.5	97.5	[illegible]	22.7	77.1	8.5
Ponderosa pine	SCD	99.8	.2	69.8	97.6	2.4	[illegible]	78.7	21.3	7.1
Ponderosa pine	SCD	99.7	.3	67.9	97.6	[illegible]	21.2	[illegible]	21.0	7.3
Ponderosa pine	SCD	99.7	.3	73.4	97.2	2.8	22.4	80.2	19.8	7.7
Lodgepole pine	SC	100.0	.0	48.6	99.1	.9	14.6	94.6	5.4	[illegible]
Lodgepole pine	SC	99.7	.3	59.8	98.7	[illegible]	18.1	95.2	4.8	8.2
Lodgepole pine	SC	99.7	.3	55.8	98.8	1.2	18.1	95.9	4.1	[illegible]
Lodgepole pine	SC	99.7	.3	54.6	99.1	.9	21.2	94.2	5.8	[illegible]

[1]Wood loss is expressed as percent of total wood input. The retained chips then amount to the percent of total chip quantities retained above the specified screen opening size. The wood and bark components are expressed as a percent of the total retained chip fraction.

[2]S = steamed 5 minutes; C = compressed; D = drubbed.

[3]0.4 percent combined bark wood not included.

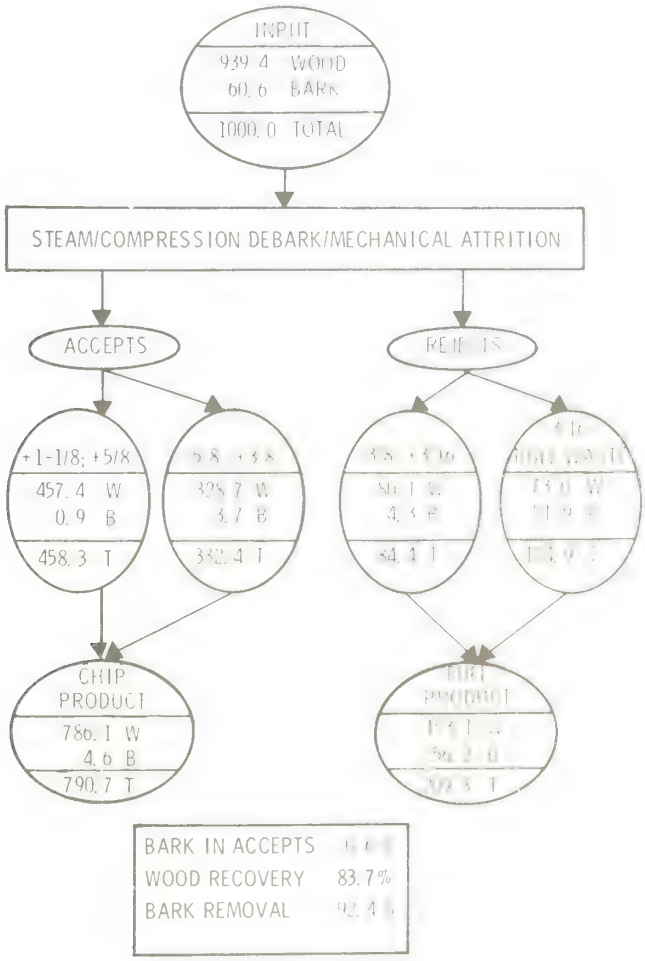


Figure 6.--Material balance for lodgepole pine (green) based on a 1,000-pound input.

3/8-inch screen after compression debarking. In summary, the material balance for lodgepole pine under the stated conditions would indicate that 790 pounds of chips would be accepted for pulping at a residual bark content of 0.6 percent. Or, 92.4 percent of the input bark was removed with 83.7 percent wood recovery.

About 210 pounds of material was rejected of which one-fourth was bark. Figure 7 shows the relative proportions of each size fraction and roll reject.

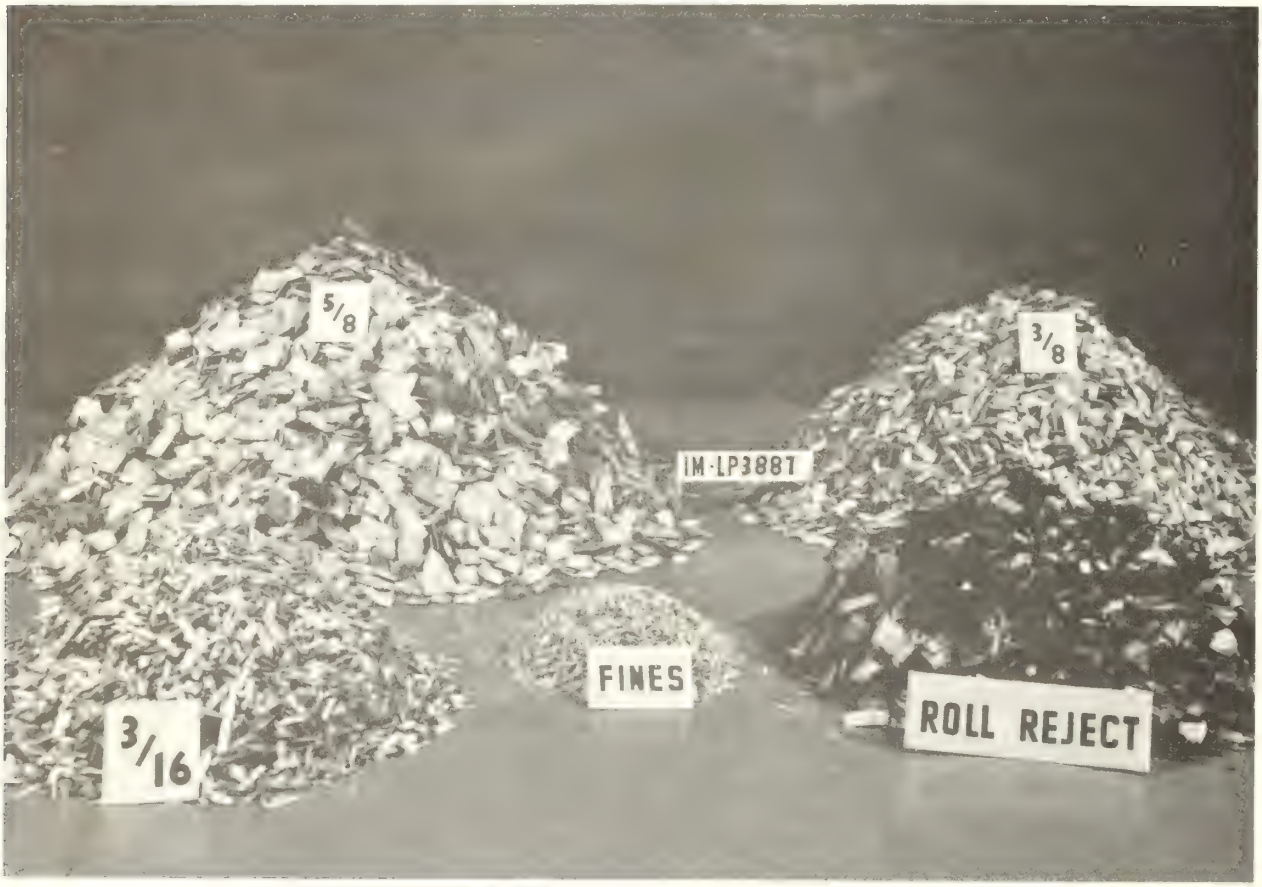


Figure 7.--Typical proportions of materials in final separation of chipped lodgepole pine.

APPLICATION OF CHIP DEBARKING TECHNOLOGY

Montana and Idaho annually produce 9 million cubic feet of chippable logging residue. Access and development costs have already been borne by the saw logs or thinning contracts. Road-access standards in many cases would permit chipping operations for the recovery of these residues. The degree of utilization of chipped residues, however, is dependent on debarking of wood chips. What then would be the impact of the chip debarking technology on the chipped residues?

The annual chippable residue of 892 million cubic feet converts to 13.4 million tons of wood and bark at 30 pounds per cubic foot, bone dry. Recognizing that it would be unrealistic as well as uneconomical to recover and process all the residue material under even the most favorable market conditions, only 10 percent, or 1.3 million tons of material will be assumed recoverable in the following example. This represents over 1 million bone-dry units at 2,400 pounds per unit.

To illustrate the impact of this chip debarking technology on Intermountain area logging operations and chip supplies, the following example is presented.

To simplify the example the following assumptions are made:

1. A modest 10 percent residue utilization level is rounded to 1.2 million tons.

2. Material loss is zero in the chipping and compression debarking processing. (All material is utilized for pulp or fuel.)

3. Accept wood chips size is +3/8 inch in the chip debarking process.

4. Wood fiber recovery from the debarking process is 80 percent.

5. The residual bark component in processed chips is as follows for total output:

Lodgepole pine	0.5 percent of wood
Ponderosa pine	1.4 percent of wood
Douglas-fir	2.3 percent of wood

6. The total residue volume of 1.2 million tons is equally distributed among the three species, lodgepole pine, ponderosa pine, and Douglas-fir.

Assuming equally proportioned distribution of the three species, table 3 shows the extrapolated recovery of saw log residues in Montana and Idaho: 843.3 thousand tons of clean chips for pulping and 357.7 thousand tons available as fuel.

Table 3.--*Annual recovery from Intermountain area saw log residue, in thousand bone-dry tons*

Residue form	Lodgepole pine	Ponderosa pine	Douglas fir	Total
	Thousand bone-dry tons			
Raw chips				
Wood	372	336	332	
Bark	28 (7%)	64 (16%)	68 (17%)	
Processed chips >3/8"				
Wood	297.5	268.8	265.5	
Bark	1.5 (0.5%)	3.8 (1.4%)	6.2 (2.3%)	
Total	299.0	272.6	271.7	843.3 70.3%
Residue				
Wood	33.8	67.3	66.4	
Bark	67.2	60.3	61.9	
Total	101.0	127.4	128.3	357.7 29.7%
Total	400	400	400	1,200 100%

1. Because chip values and fuel values vary geographically, it is impossible to give an accurate value. However, if we assume clean chips to be worth $40 per dry ton and fuels to bring $10 per dry ton, the debarked chips would have a net value of about $30.6 million after deducting an estimated $5.10 per dry ton for debarking. Barky chips would bring less than $12 million as fuel.

2. Aside from the increase in value, roundwood supplies would be extended by the equivalent of the 843,000 dry tons of usable chips, and additionally, 357,000 dry tons of fuel with a gross heat potential of about 6.1 trillion Btu would be available. For mills subject to interruptable energy supplies, this added fuel source could be important.

3. The increased value of chipped saw log debris could very easily increase salvag activity so that the utilization rate will exceed the 10 percent assumed in the example. As with primary mill residue, some of the cost of harvesting and chipping logging residue can be borne by the sawtimber operation.

4. Removal of wood residues in road construction would lower the fire risk along roads and would provide a considerable cost saving in road construction because right-of-way slash can be windrowed for removal during the chipping operation.

5. Provide incentives for multiproduct logging.

CONCLUSIONS

A system has been developed to debark chipped forest residues. Research showed that the process worked well on barky chips produced from whole trees of several tree species. The system consists of steaming, compression debarking, drubbing, and a final screening to remove fines.

The purpose of this study was to evaluate the technical feasibility of removing bark from chipped logging residues in the Intermountain area. It was found that the process definitely shows promise for upgrading a large percentage of barky chips produced from typical logging residues. Study results indicated 70 to 80 percent of the wood fiber could be recovered from freshly chipped (green) logging residue, with residual bark contents of 3 percent or less.

If only 10 percent of the available logging residues in the Intermountain region were harvested each year, more than 1.3 million dry tons of material would be available to industry. If this entire amount of material were converted to barky chips and then debarked by this system, approximately 843,000 dry tons of clean chips can be recovered for pulp and paper, and the remaining 557,000 dry tons used as fuel.

Utilization of this residue material would counteract mounting public objection to present utilization standards and disposal practices. Logging residues would be considered a resource--not waste.

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1976. Debarking chipped logging residues: technique and potential impact. USDA For. Serv. Res. Pap. INT-179, 12 p. 5 ref. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Woods-run samples of four Intermountain species (western larch, Douglas-fir, ponderosa pine, and lodgepole pine) were chipped separately, then processed through the chip debarking system developed by the Forest Service's Forest Engineering Laboratory at Houghton, Michigan. When the chips retained for each species were mixed together, bark content ranged from 1 percent for lodgepole pine to 7 percent for western larch. Bark removal ranged from 69 to 85 percent, wood loss from 8 to 13 percent.

OXFORD: 431:832, 676 1, 6.
KEYWORDS: residue utilization, cutting chip value, chip bark removal.

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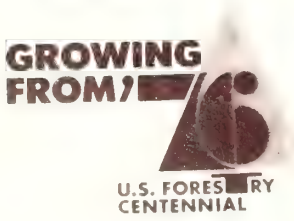
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WILDERNESS FIRE POLICY:

AN INVESTIGATION OF VISITOR KNOWLEDGE AND BELIEFS

George H. Stankey

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ABSTRACT

Discusses the attitudes and knowledge of wilderness visitors toward wilderness fire suppression policy. Although most users favored suppression, a substantial minority favored a more natural role for fire. Few found either total suppression or no suppression at all acceptable. A major finding was that as visitor knowledge about the role of fire increased, the likelihood of support for a more natural role for fire also grew. Important policy implications include educating and involving the public, making gradual changes in fire policy, and developing a communications program aimed at different audiences.

EVALUATION OF WILDERNESS FIRE POLICY

Current fire management philosophy recognizes that fire is not a recent aberration that the white man has visited upon the environment, but a natural part of our forest and rangeland ecosystems. Virtually all the northern Rocky Mountains have been burned on repeated occasions, with fires occurring on any given area about every 150 years, with a range from 10 to 300 years (Wellner 1970; Roe and others 1971). Many commercially valuable timber species as well as many other plant and animal species have evolved in the presence of fire and their continued presence is dependent upon the perpetuation of fire in the ecosystem (Mutch 1970). In the face of these realities, fire management seeks to reintroduce the beneficial aspects of fire into forest communities, including such things as maintaining young, vigorous stands capable of withstanding insect and disease outbreaks (Heinselman 1970b), reducing the excessive accumulation of forest fuels (Roe and others 1971), recycling important nutrients (Kilgore in press), and creating important wildlife habitat (Lyon 1966).

The key element in the fire management program is the land management objective; fire is a useful and beneficial ally only to the extent that it helps achieve some specific purpose. Such objectives prescribe the conditions that are desired and the means for attaining them.

In our National Parks and Wildernesses, a key management objective is the perpetuation of natural forest ecosystems (Habeck and Mutch 1973). On units of the National Wilderness Preservation System particularly, we are committed to a course of action that allows the forces of nature to operate "untrammeled by man" to maintain the natural ecosystems of these areas (Heinselman 1970a). To this end, fire management programs have been initiated in several areas. In Sequoia and Kings Canyon National Parks, lightning fires have been allowed to burn in certain zones as a means of restoring and maintaining the natural conditions of the park areas (Kilgore and Briggs 1972). Similarly, the Forest Service has initiated new policies regarding fire suppression in wilderness. In accordance with an approved plan, certain fires are allowed to burn while being kept under surveillance. Beginning in 1970, a program to provide for a more natural incidence of fire was initiated in the 100-square-mile White Cap and Bad Luck drainages of the Selway-Bitterroot Wilderness in Idaho. Since initiation of this policy, seven fires have occurred, one burning 1,200 acres (Mutch 1974).

Table 1.--*True-false test to determine level of knowledge about the role of fire in the northern Rocky Mountains*[1]

1. Forest fires usually result in the death of the majority of the animals in the area.

   Basically True Basically False Not sure

2. Most forest fires in the northern Rocky Mountains are started by lightning.

   Basically True Basically False Not sure

3. Past forest fires have not changed the way in which the northern Rocky Mountain forests developed.

   [illegible] Basically False Not sure

4. The elimination of forest fire in the northern Rockies would result in a change in the kinds of plants and animals found in the area.

   Basically True Basically False Not sure

5. Complete control of all forest fires would reduce the habitat of animals such as [illegible].

   [illegible] Basically False Not sure

6. The majority of forest fires that occurred in the Rocky Mountains before the pioneers covered hundreds of thousands of acres.

   Basically True Basically False Not sure

7. Fire often proves useful in making minerals and nutrients available to plants and trees.

   Basically True Basically False Not sure

8. Some kinds of trees found in northern Rocky Mountain forests would gradually disappear over time if all fires were eliminated.

   Basically True Basically False Not sure

9. Forest fire can be an important force in controlling outbreaks of disease and insects in forests.

   Basically True Basically False Not sure

10. Intensive fire control has actually increased rather than reduced the chances of a very large fire occurring.

    Basically True Basically False Not sure

11. Forest fires are partly responsible for some of the open meadows and grassy fields one finds in the northern Rocky Mountains.

    Basically True Basically False Not sure

[1]Correct answer for each item is underlined.

The affective domain, or how people [illegible] sion policies, was measured by use of an attitude scale based on the Social Judgment Approach (Sherif and others 1965). [illegible] encompass a range of feelings rather than a single, unwavering idea--our feelings [illegible] most things are flexible or have latitude. However, our feelings toward some [illegible] generally fall into one of three categories: (1) we accept them, (2) we reject them, or (3) we have no particular feeling about them one way or another.

In studies on how people develop attitudes about something, and particularly how those attitudes can be changed, researchers have learned certain important principles. For example, as long as a message about something remains within the broad range of acceptable feelings a person holds (a range called the "latitude of acceptance" or LOA by social psychologists), a change in attitude in the desired direction will probably occur. However, if the message begins carrying an idea that is definitely beyond the range judged acceptable by the individual (an idea that lies in the "latitude of rejection" or LOR), little or no attitude change in the desired direction can be expected. In fact, such messages may "boomerang," producing a change directly opposite to that desired (Zimbardo and Ebbesen 1970).

In applying the principles of the Social Judgment Approach to this study, we sought to define the relative range of wilderness fire suppression policies that are judged as acceptable and unacceptable.

Respondents were presented with a list of nine different statements they might adopt with regard to wildfire in wilderness (table 2). These statements ranged from

Table 2.--*Alternative wilderness fire suppression statements*

A.	It is absolutely necessary that all forest fires be put out as soon as possible in our wilderness areas.
B.	It would probably be best if all forest fires were put out as soon as possible in our wilderness areas.
C.	Generally, it would be preferable if all forest fires in wilderness were put out as soon as possible.
D.	It is hard to decide what the policy toward forest fires in wilderness should be but probably they should be put out as soon as possible.
E.	It is hard to decide whether we should allow forest fires to burn in our wilderness areas or not.
F.	It is hard to decide what the policy toward forest fires in wilderness should be but probably we should allow small, "safe" ones to burn.
G.	Generally, it would be preferable if small, "safe" forest fires were allowed to burn in our wilderness areas.
H.	It would probably be best if most forest fires were allowed to burn in our wilderness areas.
I.	It is absolutely necessary that we allow all forest fires to burn in our wilderness areas.

advocating complete suppression to advocating no suppression whatsoever. Respondents were asked to place an "X" on the statement that most nearly matched their own personal feeling. Next, they were asked to place an "O" by all other statements which were also acceptable to them. This allowed us to measure the range of acceptability. The second part of this section presented the same nine statements, but this time asked the respondent to check "√" the one statement that was most objectionable and to place a box "☐" next to all other statements that were also objectionable. This, then, gave us a measure of the range of feelings about unacceptable policies.

ATTITUDES OF WILDERNESS VISITORS

Table 3 presents the percentage of persons in our sample who answered each of the 11 test questions correctly. Two general observations may be drawn from the data. First, the general performance was poor; the average score was only 53 percent. Second, the range of correct answers on the individual items is great. For instance, 67 percent answered question 9 correctly, but only 23 percent correctly answered number 6.

The best performance was on question 3, which concerned the effect of fire on forest succession, and question 9, which was directed at the "cleansing" effect of fire on disease and insects.

During review of a draft of this manuscript for this publication, Mr. James Agee of the National Park Service correctly observed that, technically, the answer to question 3 should be false. The forests of the northern Rocky Mountains have not changed *because* of fire; they are a natural product of the fires that were part and parcel of these ecosystems. Our intent here was to address the question as to whether or not fire had played a significant role in shaping these forests. Numerous studies have documented this (for example, Habeck and Mutch 1973; Norum and others 1974), and this was the basis for our considering the statement true.

The poorest scores occurred on questions 1, 6, and 10. The content of these three questions is worth examining. Question 1 concerns the death of wildlife due to fires. Wildlife has become a central part of much of the fire prevention effort. Posters stress identity with wildlife by giving animals human characteristics: names, tears in their eyes, and so forth. However, there is little evidence that fires typically destroy large numbers of wildlife (Howard and others 1959; Cringar 1958).

It is apparent from the response to question 6 that many people see fire as a rare historical event and one which, when it did occur, was a gigantic holocaust. However, fire history studies suggest that fire was a relatively common occurrence on the landscape and moreover, that many of the fires were relatively small (Wellner 1970).

Table 3.--[illegible]

Question (Answer)	Percentage answered correctly
1. Forest fires usually result in the death of the majority of the animals in the area. (F)	[illegible]
2. Most forest fires in the northern Rocky Mountains are started by lightning. (T)	[illegible]
3. Past forest fires have not changed the way in which the northern Rocky Mountains forests developed. (F)	[illegible]
4. The elimination of forest fire in the northern Rockies would result in a change in the kinds of plants and animals found in the area. (T)	[illegible]
5. Complete control of all forest fire would reduce the habitat of animals such as elk. (T)	[illegible]
6. The majority of forest fires that occurred in the Rocky Mountains before the pioneers covered hundreds of thousands of acres. (F)	[illegible]
7. Fire often proves useful in making minerals and nutrients available to plants and trees. (T)	55
8. Some kinds of trees found in northern Rocky Mountain forests would gradually disappear over time if all fires were eliminated. (T)	[illegible]
9. Forest fire can be an important force in controlling outbreaks of disease and insects in forests. (T)	[illegible]
10. Intensive fire control has actually increased rather than reduced the chances of a very large fire occurring. (T)	40
11. Forest fires are partly responsible for some of the open meadows and grassy fields one finds in the northern Rocky Mountains. (T)	[illegible]

Finally, only 40 percent of the respondents correctly answered question 10, concerning the potential of a large fire occurring under today's intensive fire control programs. Most were apparently unaware of the fuels that have accumulated in many areas over the past 30 to 50 years. However, the right combination of factors--fuels, weather, and so forth--could lead to a fire that would be virtually beyond human control. Certainly, precautions such as aerial surveillance and quick attack lessen the chances of such a fire getting beyond controllable size, but nevertheless, the potential for such a blaze grows as fuels continue to accumulate. Our test indicates that our sample population was, to a considerable extent, unaware of the mounting fire hazard. In other words, most users believe that forests are now completely protected against holocausts.

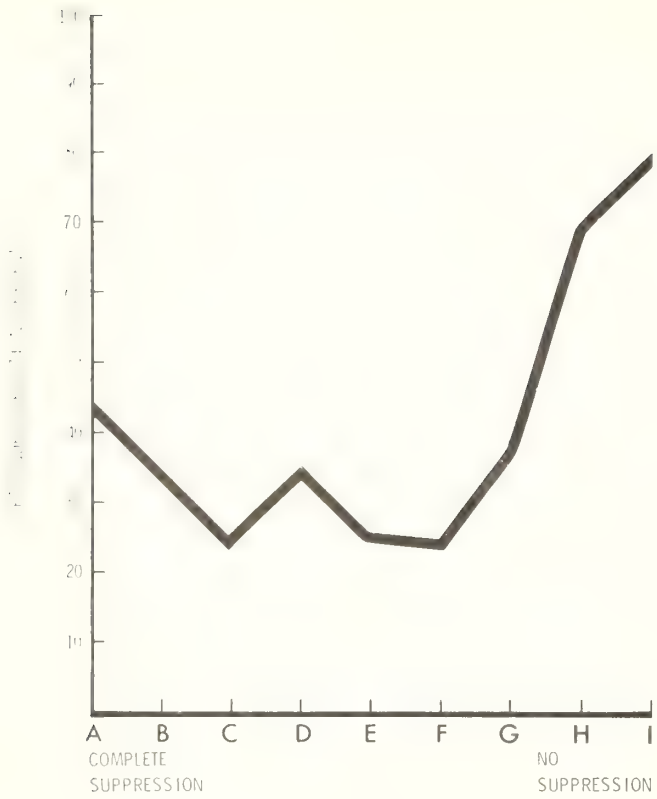

Figure 1.--Unacceptable suppression statement.

As suggested earlier, there is no single attitude about wilderness fire suppression but, rather, a range of attitudes. The nature of this range became more apparent as we reviewed responses to the nine suppression statements outlined in table 2. Figure 1 presents the response to those items defined as unacceptable. For ease of presentation, the "most unacceptable" and "also unacceptable" responses are combined. Because respondents could indicate more than one statement as unacceptable, the sum of the plotted points for each statement equals more than 100.

The respondents almost unanimously rejected the statement that we allow all forest fires to burn in our wildernesses. However, we also found a substantial proportion (43 percent) of respondents indicated that complete suppression was also unacceptable. Most persons did not find the intermediate policy positions unacceptable.

Figure 2 presents the responses as to acceptable wilderness fire suppression action. Only 5 percent found "no suppression" (statement I) acceptable. However, only about one third found complete suppression (statement A) acceptable. About one-half indicated that statements F and G were acceptable. These two statements suggested that it might be best if small, "safe" fires were allowed to run their course. The presence of the modifier "safe" might have influenced response (although it did not appear to do so in figure 1). The idea we were trying to convey in these two statements was that certain fires would be allowed to burn if they met certain criteria; in other words, that they were "safe" to let burn. There was moderate support for this concept.

Most respondents supported a narrow range of policies. As table 4 shows, fewer than two other acceptable policies were selected in addition to the "most acceptable" choice. The only exception was with statement D (mildly suppression-oriented), where persons chose almost three additional statements. We also see a slight increase in "also acceptable" policies for persons choosing statement F as "most acceptable," which called for nonsuppression in limited situations. Few persons selected statement E (a neutral position), either as "most acceptable" or as "also acceptable."

Figure 2.--Acceptability of suppression statement.

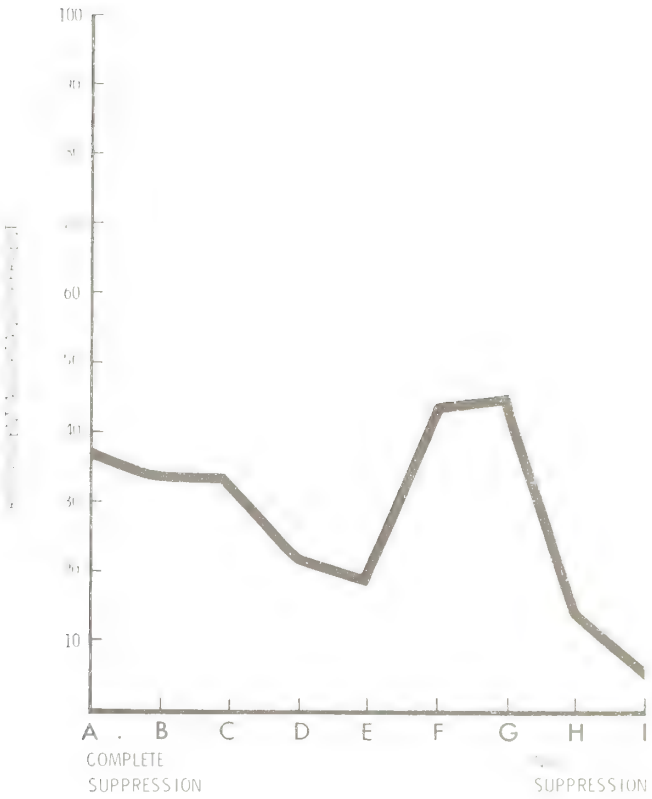

Table 4.--*Frequency of times statements cited as "most acceptable" and "also acceptable" by wilderness users*

Policy	Times cited as "most acceptable"	Total number of other policies selected as "also acceptable"	Average number of other policies cited as "also acceptable"
A (Complete suppression)	55	75	1.4
B	15	21	1.4
C	14	21	1.5
D	16	45	2.8
E	7	10	1.4
F	23	40	1.7
G	32	44	1.4
H	13	19	1.5
I (No suppression)	3	3	1.0

N = 183

Table 4 clearly indicates that suppression actions (statements A-D) were favored by more users than those favoring reduced suppression (statements F-I). Nevertheless, F-I were supported by a substantial minority; 62 percent of the "most acceptable" choices were for statements advocating suppression while 34 percent supported modified suppression.

Although table 4 shows that the average number of acceptable statements is generally narrow, it does not tell us the direction in which "also acceptable" statements tend to run relative to those selected as "most acceptable." That is to say, do those statements selected as "also acceptable" tend to lie symmetrically about the "most acceptable" choice or do they tend to be skewed to one side or the other?

In table 5, we show the frequency distribution of "also acceptable" statements for each of the nine statements. As one would expect, we see a clustering of "also acceptable" choices immediately adjacent to the one chosen as most acceptable. For example, 77 percent of "also acceptable" responses by persons selecting B as "most acceptable" were for A and C. Likewise, 80 percent of the "also acceptable" statements given by persons selecting G as "most acceptable" were for F and H. So, we see that most persons picked statements they perceived as closely similar to their most acceptable choice, certainly a logical pattern.

If we define items D, E, and F as expressing a neutral "core," persons selecting one of these as "most acceptable" generally tended to select modified suppression statements as "also acceptable"; that is, they moved to the right in table 5. This suggests that persons who have yet to firmly crystallize their opinions regarding wilderness fire suppression are likely to support some modified approach.

According to the Social Judgment theory, persons selecting extreme positions see other positions as more different than they actually are. Persons choosing A (the extreme suppression statement), however, did not meet this description. Choices of "also acceptable" statements ranged over the entire continuum. However, persons selecting I (advocating no suppression) had a very narrow LOA. The sample size here is so small (3) that we cannot tell if this response is just an accident or an actual characteristic. We do know, however, that intense commitment to a particular position tends to reduce the range of acceptable statements. A plausible explanation for the respective distributions found for statements A and I might be that while persons selecting A did so out of a "traditional" concern for fire protection, persons choosing I did so because their understanding of the situation led them to reject traditional approaches in the context of wilderness.

But there are many other plausible hypotheses as well. We have seen from the data that many attitudes about fire suppression in wilderness exist. The next question we must address is "why?" What are the critical variables that lead to this differential pattern and to what extent might managers be able to influence this pattern?

Table 5.--*Percentage distribution of statements defined as "also acceptable"*

Most acceptable statement		Other policies also acceptable								
		A	B	C	D	E	F	G	H	I
Complete suppression	A	√	40	36	11	1	4	5	1	1
	B	29	√	48	19	--	5	--	--	--
	C	10	33	√	33	--	10	14	--	--
	D	2	18	24	√	22	24	9	--	--
	E	--	--	--	10	√	50	40	--	--
	F	--	--	2	10	28	√	53	5	2
	G	-	--	2	5	14	64	√	16	--
	H	--	--	--	--	5	32	53	√	11
No suppression	I	--	--	--	--	--	--	33	67	√

N = 183

FACTORS AFFECTING ATTITUDES ABOUT WILDERNESS FIRE SUPPRESSION

Of the many factors that could affect attitudes toward wilderness fire suppression, we examined four variables: age, first-time versus repeat visits, education and score on the fire knowledge test. Using chi-square analysis, we tested for significance at the 0.05 level.

There was no statistically significant difference for the first three variables. We had hypothesized that younger visitors would be more supportive of modified suppression than would older visitors. Similarly, we speculated that persons who were repeat wilderness visitors would be more likely to support modified suppression than would first-time wilderness users. Finally, we hypothesized that persons with more education would be more supportive of modified wilderness fire suppression than those with less education. However, in all three cases, we were forced to reject our hypotheses. The pattern of support for modified suppression was irregular, complex, and unclear. At times, in fact, the data were almost directly contrary to our expectations.

The final variable was the score derived by respondents on the fire knowledge test. We hypothesized that persons scoring high on the test would tend to favor modified statements. There was a strong relationship between the test score and the statements selected as acceptable (table 6). As test scores rose, so did the likelihood that the respondent would accept a modified position. For instance, none of those scoring higher than 92 on the test found *any* of the suppression statements acceptable. Conversely, although nearly 80 percent of those scoring 35 or less found A acceptable, only 15 percent found G acceptable. This dramatic swing in the acceptability of A and G with a change in test score is graphed in figures 3 and 4, respectively.

We further examined this relationship by considering the association between the test score and the number of times a statement was selected as "most acceptable." Using gamma[2] as our statistical measure of association, we found an association of 0.57; that is, knowledge of the individual's test score explained nearly 60 percent of the variance in the selection of the "most acceptable" statement.

The test provided us with a measure of the cognitive aspects of users' attitudes about fire suppression in wilderness. As we can see from the previous discussion, the cognitive and belief domains are related. As the knowledge (as measured by our test score) increases, so does the probability that an individual will select a statement advocating a more natural role for fire in wilderness. At the same time, the relationship is not completely direct. For instance, statement I, advocating no suppression at all, is usually rejected by persons scoring high on the test.

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[2]Gamma indicates the proportional reduction in error that would occur in predicting rank order variation in preference from knowledge of the individual's test score over that which would occur without such knowledge.

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	F	--	--	2	10	28	√	53	5	2
	G	--	--	2	5	14	64	√	16	--
	H	--	--	--	--	5	32	53	√	11
No suppression	I	--	--	--	--	--	--	33	67	√

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Table 6.--*Percentage indicating statement acceptable*

Test score	N	Complete suppression A	B	C	D	Neutral E	F	G	H	No suppression I
0-35	40	78	58	55	25	18	18	15	0	0
36-44	18	56	33	39	22	17	28	33	6	6
45-54	18	50	50	44	33	17	33	22	6	11
55-63	30	37	40	50	30	20	47	33	7	0
64-72	28	18	21	29	25	29	64	64	18	0
73-81	20	10	20	25	25	25	70	80	20	5
82-91	24	4	8	13	13	25	67	83	46	17
92+	3	0	0	0	0	0	67	100	67	0

Total N = 181

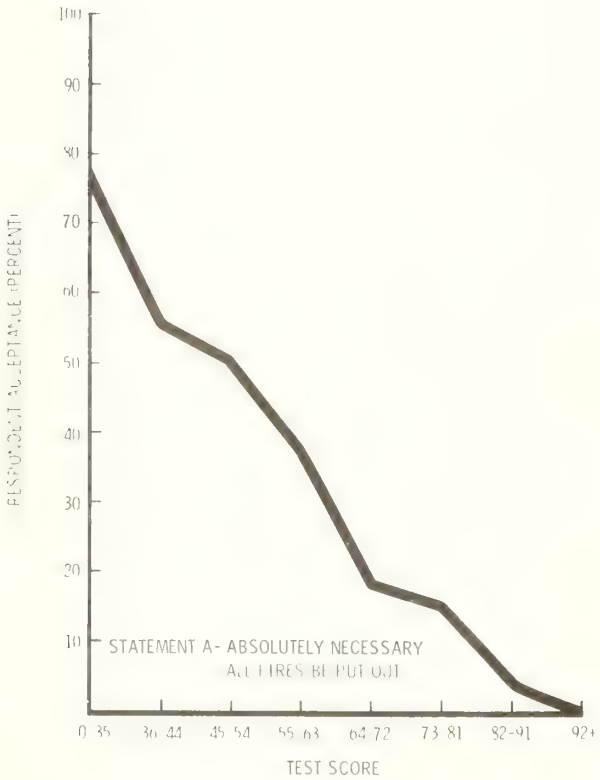

Figure 3.--Relationship between test score and percentage of respondents supporting statement A.

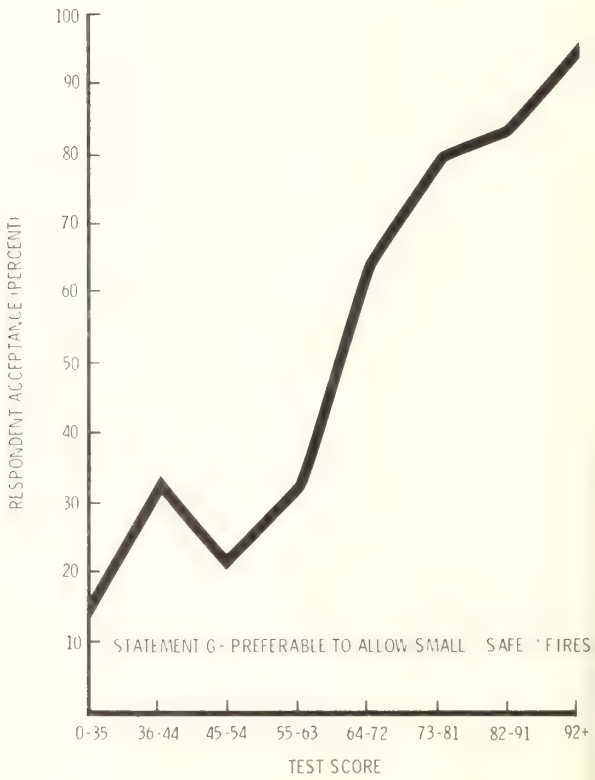

Figure 4.--Relationship between test score and percentage of respondents supporting statement G.

MANAGEMENT IMPLICATIONS

Based on this study's findings, three management actions would enhance public support for modified wilderness fire suppression.

Educate the Public

Garnering public support for modified suppression policies seems closely linked to educating the public to the role of fire in forest ecosystems. It is important that such an effort be made "across the board," not just with regard to wilderness.

As Glascock (1972) has noted, "Education is the most powerful single force deliberately used to shape public opinion toward fire."

As we discussed earlier, affect (how we feel) is not unrelated to cognition (what we believe). This was clearly the case in this study. Persons who understood little about fire were much more likely to endorse stringent suppression statements than were those better informed. Efforts to gain public support, in the absence of concomitant programs to educate, inform, and involve people, seem doomed to failure.

Both administrative guidelines as well as laws such as the National Environmental Policy Act have defined increasingly significant roles for public participation in resource decisionmaking. In particular, such participation serves the function of defining the normative goals toward which our resource management programs should strive. However, if the public is expected to provide realistic and reasonable goals for resource managers to achieve, they must have accurate information. We simply cannot expect useful citizen participation in decisionmaking when the base of information the citizen is using (a base generally supplied by the resource management agency) is faulty or incomplete. We have seen the low level of knowledge that wilderness users possess; it is probably reasonable to assume an even lower level exists among the general public. We should consider the lack of knowledge a major reason for improving the flow and quality of information.

There has been some concern that anything short of an "every fire out immediately" philosophy might lead to increased careless use of fire by people using the forests. However, there seems little basis for the concern. In many ways it is an affront to the public to suggest that it is incapable of distinguishing between the use of fire to accomplish specifically stated objectives and its illegal, indiscriminate use. At any rate, the failure to disclose the facts about fire, or the exaggeration or distortion of the nature of fire will do little to promote desired behavior on the part of the public about fire. "Scare" tactics in fire control literature probably have little effect in reducing fires. The use of similar techniques as methods to control such problems as drug abuse have been unproductive.

Davis' (1959) remarks about the importance of frankness in dealing with the public are appropriate:

> Very real problems of education and understanding are involved in distinguishing between undesirable wildfires and desirable uses of fire in certain situations. But the truth will come out sooner or later: Fire does have uses. It is better to meet such questions honestly and squarely, but with discretion, than to risk the consequences of lack of public confidence resulting from unwillingness to face up to the matter.

Avoid Sudden Changes in Policy

Most users indicated support for suppression-oriented statements. Moreover, the latitude of acceptable policies was generally quite narrow. Thus, programs that call for a sudden shift in policy direction would appear to have considerable potential for creating a "boomerang" effect, in which increased agency efforts to push modified suppression might be greeted by stiffened public resistance.

The theory of Social Judgment predicts the greatest attitude change when a message advocates a position at the extreme boundary of an individual's latitude of acceptance. The data presented here aggregate individual responses, but we can see how programs endorsing a substantial and rapid change in wilderness fire suppression would be at odds with most users' attitudes. Thus, we find support for a gradual, or incremental, approach to altering wilderness fire suppression policy.

Under a gradual approach, the new fire policy might be initially limited to a few areas, the number of acres within any one area would be limited, and certain restrictions would be established for when and where fire would be permitted. For instance, weather conditions or the burning index might be major determinants on whether or not a fire would be allowed to burn. As experience with fire increases and as public awareness of such programs grows, the number of areas and acres covered by modified policies might gradually be increased.

Such an approach does pose problems for the resource manager. Attempting to initiate and conduct a fire management program on too small an area can generate disproportionately high costs as well as other problems. For example, one of the fires that started in the fire management prescription zone in the White Cap drainage of the Selway-Bitterroot Wilderness spotted across into an area not under prescription and burned approximately 1,600 acres. Although our knowledge of fire behavior is improving constantly, such outbreaks and unexpected fires are going to happen. During the preliminary stages of introducing a new policy direction, however, managers will need to walk the tight line between excessive enthusiasm that might confuse and worry the public, on the one hand and, on the other hand, experimenting on such a limited scale that they impose unrealistic constraints upon themselves, hindering the opportunity for a fair and reasonable test.

Educate all Segments of the Public

The diversity of opinion in the homogeneous population of wilderness users suggests that a survey of the general public would reveal even greater diversity. As we attempt to garner support for modified fire suppression across a broader spectrum of the public we will need a variety of tools to contact diverse publics. Even wilderness users are different enough to require ingenuity and imagination to reach them all. Working through conservation and outdoor recreation groups is important; however, this should not be relied upon as the sole source of contact with users. We found only 27 percent of the respondents indicated membership in such groups. Visits by users to ranger stations, field contacts by wilderness rangers, and the use of handout materials (maps, information brochures, etc.), should all be viewed as opportunities to communicate information to visitors.

Educating the "general public" presents more formidable problems than educating wilderness users. The data in this study do not bear directly on this issue, but they do suggest that the content of communications should be factual and straightforward. Given the diverse nature of the "general public," a similarly diverse package of communication programs seems called for, varying in the level of presentation and in the medium. Programs in the schools, presentations to service clubs, and newspaper and television features are only a few of the ways in which this "general public" might be reached.

We should also consider all other fire prevention materials. Although our investigation did not attempt to trace where people got their information, it seems reasonable that fire prevention posters and literature are an important influence on public attitudes, and therefore we should consider the messages they communicate.

In our efforts to educate the public to be careful in the use of fire, we do not want to foster public resistance to other programs we are attempting to implement. Also, if the public comes to believe that fire prevention materials are inaccurate or nonfactual, they may decide that there is no need to be careful with fire.

SUMMARY

This study has investigated the attitudes and beliefs of wilderness users toward modified fire suppression in wilderness. The results suggest that while a majority of users favor suppression, a substantial minority support a more natural role for fire. Few users found either total suppression or no suppression at all acceptable.

Most users revealed a fairly low level of understanding about the role of fire in the forests. On investigating the relationship between attitudes about fire suppression in wilderness and knowledge, there was a strong association between higher knowledge scores and support for liberalized suppression. Age, membership in conservation groups, and previous wilderness experience were found to have no significant effect on this relationship.

As land management agencies strive to gain public support for modifying wilderness fire suppression policies, three important implications seem to emerge from the data. They include: (1) educating and involving the public; (2) gradual changes in policy; and (3) a communications program aimed at many different audiences.

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1976. Wilderness fire policy: an investigation of visitor knowledge and beliefs. USDA For. Serv. Res. Pap. INT-180, 17 p. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Discusses the attitudes and knowledge of wilderness visitors towards wilderness fire suppression policy. Although most users favored suppression, a substantial minority favored a more natural role for fire. Overall, other forms of suppression or no suppression at all were acceptable. Another finding was that a positive knowledge about the role of fire increased the likelihood of support for a more natural role for fire to occur. Opportunities for implementing and improving the public contact program and its effectiveness.

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AMERICAN REVOLUTION BICENTENNIAL
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GROWING
FROM
U.S. FORESTRY
CENTENNIAL

LOGGING RESIDUES UNDER DIFFERENT STAND AND HARVESTING CONDITIONS, ROCKY MOUNTAINS

obert E. Benson and
ameron M. Johnston

USDA Forest Se
Research Paper INT-181
INTERMOUNTAIN FOREST AND
RANGE EXPERIMENT STATION

LOGGING RESIDUES UNDER DIFFERENT STAND AND HARVESTING CONDITIONS, ROCKY MOUNTAINS

Robert E. Benson

and

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ABSTRACT

Volume and characteristics of logging residues from 34 harvest areas are presented. Clearcuts and partial cuts logged to conventional utilization levels and to close utilization levels are included. Residue volumes ranged from almost 3,600 ft^3/acre of wood 3-inches-plus down to about 550 ft^3/acre, depending on treatment. More than 60 percent of the residues were sound. A high proportion of residues were in pieces under 9 feet in length.

INTRODUCTION

Much of the merchantable-size timber in the Northern Rocky Mountain States is in mature and overmature stands. Consequently, timber harvesting in these stands over the next several decades will involve handling sizable volumes of material such as dead trees, down material, and small, understory trees that are part of most mature stands. The volume and utilization potential of this "residue"--material other than green saw logs--is of immediate interest to both the wood products industry and the land manager. To the industry this residue represents a potential source of wood fiber to help offset increasingly tight saw-log supplies. To the land manager, utilization of this material can reduce the costs of postharvest treatments.

This paper describes postharvest residues from 34 typical logging units in the Northern Rockies. Some of the units were logged to conventional utilization standards, other units or subunits were logged to more intensive utilization standards.

Volumes and characteristics of residues can vary considerably from those reported here. However, these initial data should provide a general idea of the amounts and characteristics of residues left after logging. In addition, we hope that this paper will stimulate managers to make their own evaluations of logging residues.

METHODS FOR ESTIMATING RESIDUE VOLUME

The methods used in estimating residue volumes are based on a planar intercept technique: the measuring of pieces of down material that pass through an imaginary vertical plane superimposed along a random bearing from a sample point (fig. 1). This procedure has been developed by the Northern Forest Fire Laboratory for measuring fuel loadings.[1,2] To this basic procedure we have added a more detailed description of characteristics that affect utilization potential: size of piece, species, defect, bark, and spiral grain (procedures on file at Forestry Sciences Laboratory, Missoula, Montana).

Sampling procedure in these studies has been to establish a grid of about 25 to 0 samples in each logging unit (units were generally about 20 to 50 acres in size). ach sample was a line consisting of several segments. Fine material up to 1-inch iameter was measured on a 6-foot segment of the line; larger material from 1- to 3-inch iameter was measured on a 10-foot segment; and material over 3-inch diameter was easured on a longer segment usually 35 or 50 feet in length, depending on the amount

[1]Brown, James K. 1971. A planar intersect method for sampling fuel volume and urface area. For. Sci. 17(1):96-102.

[2]Brown, James K. 1974. Handbook for inventorying down woody material. USDA For. erv. Gen. Tech. Rep. INT-16, 24 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

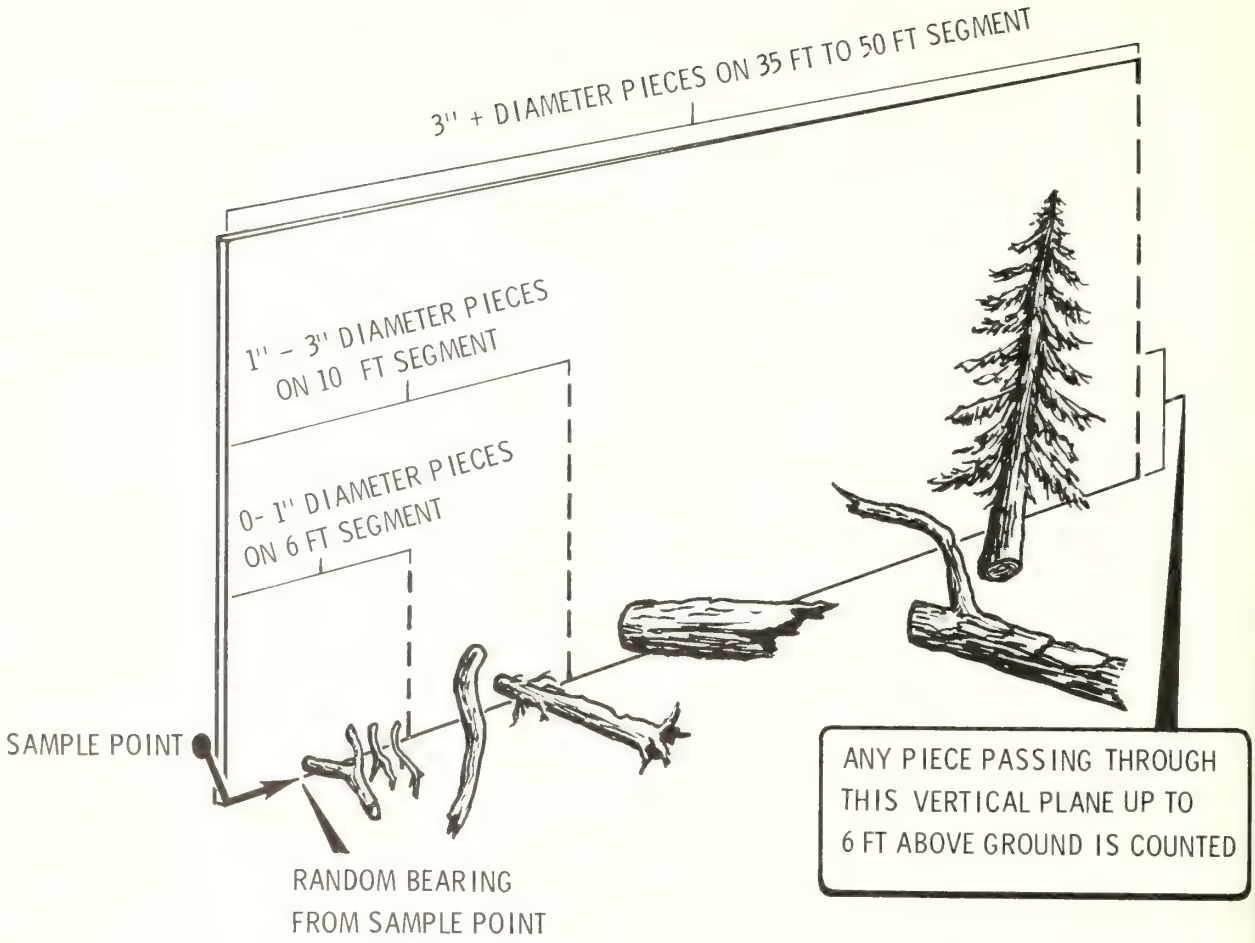
3" + DIAMETER PIECES ON 35 FT TO 50 FT SEGMENT
1" – 3" DIAMETER PIECES ON 10 FT SEGMENT
0- 1" DIAMETER PIECES ON 6 FT SEGMENT
SAMPLE POINT
RANDOM BEARING FROM SAMPLE POINT
ANY PIECE PASSING THROUGH THIS VERTICAL PLANE UP TO 6 FT ABOVE GROUND IS COUNTED

Figure 1.--Planar intercept layout.

of down material. A similar technique using a continuous transect line is also available,[3] but we have used the grid system because it better served other measurement needs of the studies.

Residue volumes were predicted by estimating the volume that would remain after logging, given the harvesting method and utilization level used on the area. This included (a) nonmerchantable material that was on the ground prior to harvest (not available on some areas), (b) cull and other nonmerchantable volume shown in the timber sale cruise data, and (c) volume of top boles from merchantable trees harvested, and from small stems, based on stand tables from sale cruise data. These predictions are compared to actual residues in tables that follow.

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[3]Howard, James O., and F. R. Ward. 1972. Measurement of logging residue--alternative applications of the line intersect method. USDA For. Serv. Res. Note PNW-183 8 p. Pac. Northwest For. and Range Exp. Stn., Portland, Oreg.

The data were punched onto cards and processed by computer through the Northern Forest Fire Laboratory. However, the formulas presented in Brown's "Handbook" are simple enough that the basic volume computations could be made with a desk calculator. The description of larger pieces in terms of utilization potential involved more complex computer procedures developed by Johnston, and these are on file at the Northern Forest Fire Laboratory.

AREAS STUDIED

Residue volumes were measured on logged units in mature lodgepole pine, Douglas-fir/larch, and mixed-conifer stands throughout Wyoming, Montana, and Idaho. On areas where intensive logging research was being done, both preharvest and postharvest residues were measured in detail. In other areas, preharvest measurements could not be made, but by piecing together timber-sale appraisal and other data we have developed an estimate of preharvest volumes. A variety of silvicultural prescriptions, harvesting systems, and utilization levels are represented by the study areas.

1. LOGGING RESIDUES — CLEARCUTS LOG

STUDY AREAS:

LODGEPOLE PINE STANDS

1. *Bridger-Teton National Forest, Wyoming.*--Mature lodgepole pine stands harvested with ground-skidding equipment. Green saw logs were removed to a 6-inch top diameter; remaining material piled and burned.

DOUGLAS-FIR/LARCH STANDS

1. *Lolo National Forest, Montana.*--Mature Douglas-fir/larch stands harvested with jammer and tractor-skidding equipment. Green saw logs were utilized from trees 9 inches d.b.h. and larger to an 8-inch top diameter; dead material 50 percent or more sound was removed; remaining material slashed.

2. *Coram Experimental Forest, Montana.*--Mature Douglas-fir/larch stands harvested with running skyline system under (1) block clearcut and (2) group selection clearcut prescriptions. Green and recently dead saw logs utilized from trees 7 inches d.b.h. and larger to a 6 inch top diameter with pieces one-third or more sound removed. Remaining material slashed.

MIXED-CONIFER STANDS

1. *North Idaho State lands.*--Mature mixed-conifer stands harvested with ground-skidding equipment. Logs utilized from trees 10 inches d.b.h. to a variable top diameter, depending on log length. Pieces one-third or more sound removed (minor variations in these specifications between units). Remaining material slashed.

ONVENTIONAL UTILIZATION STANDARDS

Figure 2.--Residue remaining after clearcut logged to conventional utilization standards, lodgepole pine.

RESIDUES REMAINING

	Preharvest volume		Predicted[1] residue,	Actual residue	
	Saw log	Total, 3 inches+	3 inches+	3 inches+	Fines
	M BF/a	*[illegible]*	*[illegible]*	*[illegible]*	*[illegible]*
LODGEPOLE PINE					
1	27.7	10,164	3,524	3,567	12.8
DOUGLAS-FIR/LARCH					
1	18.1	5,575	2,577	2,756	8.9
2	21.5	6,970	3,051	2,371	11.0
MIXED CONIFER					
1	24.0	7,947+	3,946+	3,111	10.6
AVERAGE, ALL	22.8	7,664	3,274	2,958	10.8

[1] Based on preharvest measurements and utilization specifications.
[2] Estimated from limited preharvest data; an undetermined volume of down material not included.

2. LOGGING RESIDUES – PARTIAL CUTS LOG

STUDY AREAS

DOUGLAS-FIR/LARCH STANDS

1. *Lolo National Forest overwood removal*.--Mature Douglas-fir/larch overwood harvested with jammer and tractor skidding. Green saw logs from trees 9 inches d.b.h. and larger were removed to an 8-inch top diameter; dead material 50 percent or more sound removed.

2. *Salmon National Forest overwood removal*.--Mature Douglas-fir/ponderosa pine overwood removed by helicopter.

3. *Lolo National Forest shelterwood*.--Mature Douglas-fir/larch was harvested with tractor and jammer skidding; selected shelterwood trees left; green saw logs from trees 9 inches d.b.h. and larger were removed to an 8 inch top diameter; dead material 50 percent or more sound removed.

4. *Coram Experimental Forest shelterwood*.--Mature Douglas-fir/larch harvested, with trees 7 inches d.b.h. and larger cut; green saw logs to 6-inch top diameter and dead material one-third or more sound removed.

MIXED CONIFER STANDS

1. *North Idaho State lands*.--Mixed-conifer stands about 60 to 100 years old were commercially thinned with ground-skidding equipment; about half of standing trees removed. Cut trees were 9 inches d.b.h. and larger; logs to 6-inch top removed; some dead material and cedar poles also removed.

ONVENTIONAL UTILIZATION STANDARDS

Figure 4.--A "turn" of logs coming to landing in a partial-cut, larch/Douglas-fir stand logged to conventional utilization standards.

	Preharvest volumes				Actual residue	
	Saw log	Cut volume	Total 3 inches+	Predicted[1] residue	3 inches+	Fines
	M BF/a	*M BF/a*	*Ft³/a*	*Ft³/a*	*Ft³/a*	*Tons/a*
DOUGLAS-FIR/LARCH						
1	27.7	10.7	6,611	1,328	1,532	8.8
2	- - - - - - - -	-not available-	-	- -	1,359	5.4
3	36.1	20.5	8,695	2,134	2,319	5.4
4	15.3	6.2	7,452	3,846	1,938	10.2
MIXED CONIFER						
1	[2]13.1	9.2	[2]4,362	1,518	2,860	8.7
AVERAGE, ALL	23.0	11.6	6,780	2,206	2,002	7.7

[1] Based on preharvest measurements and utilization specifications.
[2] Estimated from limited preharvest data; an undetermined amount of down material not included.

3. LOGGING RESIDUES – CLEARCUTS LOGGE

STUDY AREAS

LODGEPOLE PINE STANDS

1. *Bridger-Teton National Forest.*--Mature lodgepole pine was harvested using a feller-buncher, grapple skidder, and portable chipper. Green saw logs were removed to a 6-inch top diameter and all other material down to 3-inch diameter by 8-foot length was field-chipped.

2. *Bitterroot National Forest.*--An overmature, high-elevation stand was harvested using small, rubber-tired skidders, small crawler tractors, and horse skidding. Sound material 3-inch-plus diameter, live and dead, was removed for saw logs, houselogs, posts, and corral poles.

DOUGLAS-FIR/LARCH STANDS

1. *Coram Experimental Forest close log utilization.*--Mature stands harvested with running skyline. Trees 7 inches d.b.h. and larger were cut; all pieces green and dead, one-third or more sound, down to 3-inch diameter by 8-foot length removed. Understory protected in skidding.

2. *Coram Experimental Forest close tree and log utilization.*--Mature stands harvested with running skyline. Trees 5 inches d.b.h. and larger cut; all pieces dead and green, one-third or more sound, down to 3-inch diameter by 8-foot length removed. Understory slased for burning.

3. *Coram Experimental Forest fiber utilization.*--Mature stands harvested with running skyline. All stems 1-inch diameter and larger cut and removed; 1- to 5-inch diameter material was cut and bundled prior to logging to facilitate yarding.

SE UTILIZATION STANDARDS

Figure 4.--Field chipping residue in lodgepole pine stand logged to close utilization standards.

	Preharvest volume				
	Saw log	Total 3 inches+	Predicted[1] residue	Actual residue 3 inches+	Fines
	M BF/a	*Ft³/a*	*Ft³/a*	*Ft³/a*	*Tons/a*
LODGEPOLE PINE					
1	24.1	9,673	595	731	10.5
2	5.2	4,973	1,998	1,442	(not avail.)
DOUGLAS-FIR/LARCH					
1	20.3	7,534	2,362	1,424	11.1
2	22.0	8,137	2,835	1,983	11.5
3	15.6	6,297	2,630	1,214	8.3
AVERAGE, ALL	17.0	7,123	2,084	1,359	10.3

[1] Based on preharvest measurements and utilization specifications.

4. LOGGING RESIDUES – PARTIAL CUTS LOG

STUDY AREAS

DOUGLAS-FIR/LARCH STANDS

1. *Coram Experimental Forest close log utilization.*--Mature stands were harvested with skyline; shelterwood prescription with about half of overwood volume left. Trees 7 inches d.b.h. and larger were cut; all pieces green and dead, one-third or more sound, down to 3-inch diameter by 8-foot length removed. Understory protected.

2. *Coram Experimental Forest close tree and log utilization.*--Mature stands harvested with skyline; shelterwood prescription with about half of overwood volume left. Trees 5 inches d.b.h. and larger cut; pieces dead and green, one-third or more sound, down to 3-inch diameter by 8-foot length removed. Understory slashed for burning.

3. *Coram Experimental Forest close fiber utilization.*--Mature stands harvested with skyline; shelterwood prescription with about half of overwood volume left. All stems 1-inch diameter and larger cut and removed; 1- to 5-inch diameter material cut and bundled prior to logging to facilitate yarding.

MIXED-CONIFER STANDS

1. *North Idaho State lands commercial thinning.*--Small sawtimber stand thinned with ground-skidding equipment. About half of volume left; pieces down to 3-inch top diameter by 8-foot length removed.

LOSE UTILIZATION STANDARDS

Figure 5.--Shelterwood cut with close utilization in larch/ Douglas-fir stand.

RESIDUES REMAINING

	Preharvest volume			Predicted[1] residue,	Actual residue	
	Total volume	Cut volume	Total 3 inches+	3 inches+	3 inches+	Fines
	M BF/a	*M BF/a*	*Ft³/a*	*Ft³/a*	*Ft³/a*	*Tons/a*
DOUGLAS-FIR/LARCH						
1	9.7	5.3	5,940	2,030	1,502	9.4
2	16.4	9.1	7,397	2,664	1,610	2.4
3	14.6	6.7	5,938	2,193	865	6.4
MIXED CONIFER						
1	16.3	8.0	3,620	620	548	6.4
AVERAGE, ALL	14.2	7.3	5,723	1,877	1,151	6.2

[1] Based on preharvest measurements and utilization specifications.

VOLUME OF RESIDUES

The volume of residues 3 inches and larger remaining after logging ranged from more than 3,567 ft^3/acre in a mature, lodgepole pine clearcut unit with conventional utilization, to 548 ft^3/acre in a young, mixed-conifer commercial thinning unit where "close" utilization was practiced (tables, pages 5, 7, 9, 11).

The volume of residues was largest in clearcut units with conventional utilization (average 2,958 ft^3/acre) and smallest in partial cuts with close utilization (average 1,131 ft^3/acre). It should be noted, however, that some individual areas with close utilization had as much residue as some areas with conventional utilization. This is because of differences in initial stand volumes and also because utilization specifications were not always followed exactly--both underutilization and overutilization occurred.

Residue under 3-inch diameter--"fines," measured in tons per acre--were heavier in the clearcut areas than in partial cuts. This is to be expected because in most clearcuts small stems and defective trees were knocked down or slashed after logging.

On the average, residue volumes were less than we had predicted, based on preharvest estimates of existing residues, and slash that would be created in logging:

Area	*Actual residues as percent of predicted*	
	Average	*Range*
Clearcut/conventional	91	72 to 107
Partial cut/conventional	91	50 to 188
Clearcut/close	65	46 to 123
Partial cut/close	61	39 to 88

The conventional utilization areas had residue volumes that were closest to our predictions. On close utilization areas the loggers removed even more than we had anticipated However, this was mainly on the Coram study area, where most of the close utilization units were located. This was a closely monitored research study with some unusual logging requirements, and this probably led to more material being yarded than the specifications called for.

Variables such as habitat type, slope, logging equipment, and logging-layout specifications probably have some effect on residue volumes. However, there were not sufficient replications in the sample to draw any conclusions. (Data from individual logging units would be too lengthy to report here, but are on file at the Forestry Sciences Laboratory.)

CONDITION, SIZE, AND TYPE OF RESIDUES

In addition to volume, the soundness and size of pieces (along with species) determines the utilization potential of residues.

We sorted residues into four soundness or condition classes:

Crumbly rot--the piece could not be handled;

Solid rot--rotten, but it would hold together in yarding and handling;

Sound defect--no rot, but it has deformities, splits, etc., that prevent it from use as a roundwood product;

No defect--none of the above defects.

The actual volume of residues in different condition classes varied along with total volume; therefore proportions of residue in each class are used as a basis for comparison. We found that conventional utilization areas had much higher proportions of sound residues than did close utilization areas:

	Conventional	*Close*
	Percent	*Percent*
Crumbly rot	20	40
Solid rot	19	33
Sound defect	11	10
No defect	50	17
	100	100

To the extent that it may be possible to retrieve all residues, close utilization appears to substantially increase the recovery of sound materials. From a practical standpoint, the feasibility of recovering more material depends partly on the size of the pieces. We have determined the size distribution of sound pieces from some (not all) of the study areas. Based on these areas, most of the sound volume is in pieces under 9 feet in length (about 9 feet is needed to square the ends and produce an 8-foot

stud log or a 100-inch pulp bolt). Conventional utilization units had a higher proportion of long lengths than did close utilization units:

Piece size, sound pieces Length, small-end diam.	Conventional Percent of volume	Close Percent of volume
0 to 9 feet long		
3- to 6-inch diameter	37	45
6-inch-plus diameter	44	48
9 to 18 feet long		
3- to 6-inch diameter	9	4
6-inch-plus diameter	4	1
19-feet-plus long		
3- to 6-inch diameter	4	1
6-inch-plus diameter	2	1
	100	100

Sometimes managers are interested in knowing just how much green residue material is created in logging. On most units we identified residues as green (freshly created by harvesting operation) or dead. We found that nearly half the volume in conventional logging units is green, but only a small amount of green material was left in close utilization units:

	Dead Percent	Green Percent
Conventional utilization		
Partial cuts	56	44
Clearcuts	51	49
Close utilization	88	12

This was expected because although close utilization specifications for dead material varied somewhat, they always called for removal of sound green pieces down to 4- or 3-inch diameter.

SUMMARY AND DISCUSSION

This report presents the initial summaries of some of the basic residue data we have compiled to date. Additional detailed information on file, such as on bark volume, species, and product potential, remains to be analyzed, and will be published in future reports.

We have summarized highlights of this report in terms of questions we have been asked most frequently since we have begun quantifying residues.

1. *What volumes of residues remain after logging?*--This varies by species, utilization specifications, and a number of other factors. On the average we found about 35 percent of the initial cubic volume (3-inch-plus) of the stand remained as residue following conventional utilization; and about 20 percent of the initial volume where closer utilization was practiced (tables, pages 5, 7, 9, 11). In terms of actual volumes, clearcutting with conventional utilization averaged about 3,000 ft^3/acre of residues, and partial cutting with conventional utilization averaged about 2,000 ft^3/acre.

2. *Can residue volumes be predicted?*--Using standard timber-sale data, plus some additional preharvest measurements of down material we developed estimates that fairly accurately predicted residues in conventionally logged areas. Under close utilization, and under research study conditions, we generally overestimated the amount residue remaining. This was primarily because logging removed more than was called for in the specifications.

3. *What is the condition of logging residues?*--Condition varies with original stand conditions, but on the average, we found that under conventional utilization over 60 percent of the residue had no rotten defect. Nearly half the residue that had rot was solid enough to be handled and was potentially usable for pulp, fuel, or fiber products.

4. *Are residues recoverable and utilizable?*--A high proportion of residues appear to be sound enough for either fiber or roundwood-product use. Over 80 percent of the sound pieces are under 9 feet long, the current minimum length for products such as stud logs, pulp bolts, and house logs. Shorter pieces would be usable for fuel and fiber products, although yarding and handling them may pose some technical and economic problems. Developing logging procedures that would reduce breakage might be a partial solution.

Benson, Robert F., and Cameron M. Johnston
1976. Logging residues under different stand and harvesting conditions, Rocky Mountains. USDA For. Serv. Res. Pap. INT-181, 15 p. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Volume and characteristics of logging residues from 34 harvest areas are presented. Clearcuts and partial cuts logged to conventional utilization levels and to close utilization levels are included. Residue volumes ranged from almost 3,600 ft^3 acre of wood 3-inches-plus down to about 550 ft^3 acre, depending on treatment. More than 60 percent of the residues were sound. A high proportion of residues were in pieces under 9 feet in length.

OXFORD: 332.3, 331, 432.16
KEYWORDS: logging, slash, fuels, harvest systems, residue

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MATCHACURVE — 4:

Segmented Mathematical Descriptors for Asymmetric Curve Forms

Chester E. Jensen

USDA Forest Service Research Paper INT - 182
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

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Segmented Mathematical Descriptors for Asymmetric Curve Forms

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ABSTRACT

Methods are shown for achieving sensitivity in mathematically describing asymmetric curve forms. Independent, but compatible, descriptors are developed for each of several response surface regions or segments, in the examples given. The methods are analogous for problems necessitating the use of additional segments and/or dimensions.

INTRODUCTION

Mathematical description of asymmetric curve forms expected in a regression relation can be difficult when descriptor components must apply over the entire range of each independent variable involved. Under such constraint, failure of the analyst to find suitably accurate forms (Bartlett [1947] and Draper and Hunter [1969] recognized the necessity for allowing the analyst to establish his own acceptance criteria) among his available alternatives might prompt adoption of a segmented descriptor system. For our purposes, a segmented descriptor system is one wherein the relation to be described is divided into two or more segments covering the ranges of one or more independent variables. A descriptor is developed for the portion of the response curve within each segment and applies there exclusively. The contiguous array of these segments then portrays the entire relation. The segmented approach might be regarded as less elegant, perhaps, from the standpoint of mathematical and statistical manipulability, but this may be a necessary trade-off for descriptor accuracy.

Segmented descriptors are developed for several three-dimensional relations using systems outlined in Matchacurves-1 and -2 (Jensen and Homeyer 1970, 1971) and in Matchacurve-3 (Jensen 1973). The first example involves a two-segment descriptor. At the time of analysis, the general form of the relationship was known. A bell-shaped curve, possibly asymmetric, was expected over the range of one independent variable, while a sigmoidal curve was expected over the second. Strong interaction was likely to occur between the independent variables.

Specification of a viable mathematical hypothesis for this potentially complex form, from prior knowledge alone, was considered to be impractical. And, rather than dedicate the data to the statistical evaluation of poorly specified hypotheses and suffer a potential loss of information, the analyst elected to exhaust the data graphically. The graphed model was then described mathematically. The resulting function was refitted to response values at 36 control points on the graph, this by least squares in the simple model....

$$Y = \beta\ (\text{model transform}) + \varepsilon$$

Example #2, a three-segment descriptor, was completely specified in graphic form from prior knowledge. The objective here was simply to describe the graphed model mathematically, using the Matchacurve system. Data were not involved.

Both the graphic and general mathematical forms of these models are presented in the text. Familiarity with the Matchacurve system will enhance understanding of the segmentation adopted. Specific mathematical forms and associated explanatory material are given in the appendix to reinforce the reader's knowledge, as needed, of mathematical component development by means of Matchacurve.

EXAMPLE 1
AN ASYMMETRICAL, BELL-SHAPED RIDGE: TWO SEGMENTS

In this descriptor, tree mortality percent in a western forest is characterized by tree diameter (d.b.h.) over the course of a beetle epidemic (fig. 1). The descriptor is applicable only at discrete points in time and at the midpoints of 2-inch d.b.h. classes. Both variables are treated as continuous. As was evident in the original data, the more-or-less bell-shaped trends over time differ substantially on either side of the central ridge. For example, observe strong asymmetry at d.b.h. = 12 to 18 inches, made most noticeable perhaps by elevational differences in the curves at their left and right extremes. See also the dwindling breadth of curve crowns above and below 14 inches d.b.h., an interactive change included in the descriptor along with asymmetry. Descriptor components were assembled as follows:

Left and right sides of the ridge were described separately (fig. 2 and 3), using sigmoids from Matchacurve-1 that varied in shape and scale according to data trends over d.b.h. Because the lower portion of the left half asymptoted at values larger than zero, it was necessary to include the left-edge intercept, Int, (or floor) upon which the left-side sigmoids rested conceptually. Int is a function of d.b.h. as is the location of the ridge in time, XP.

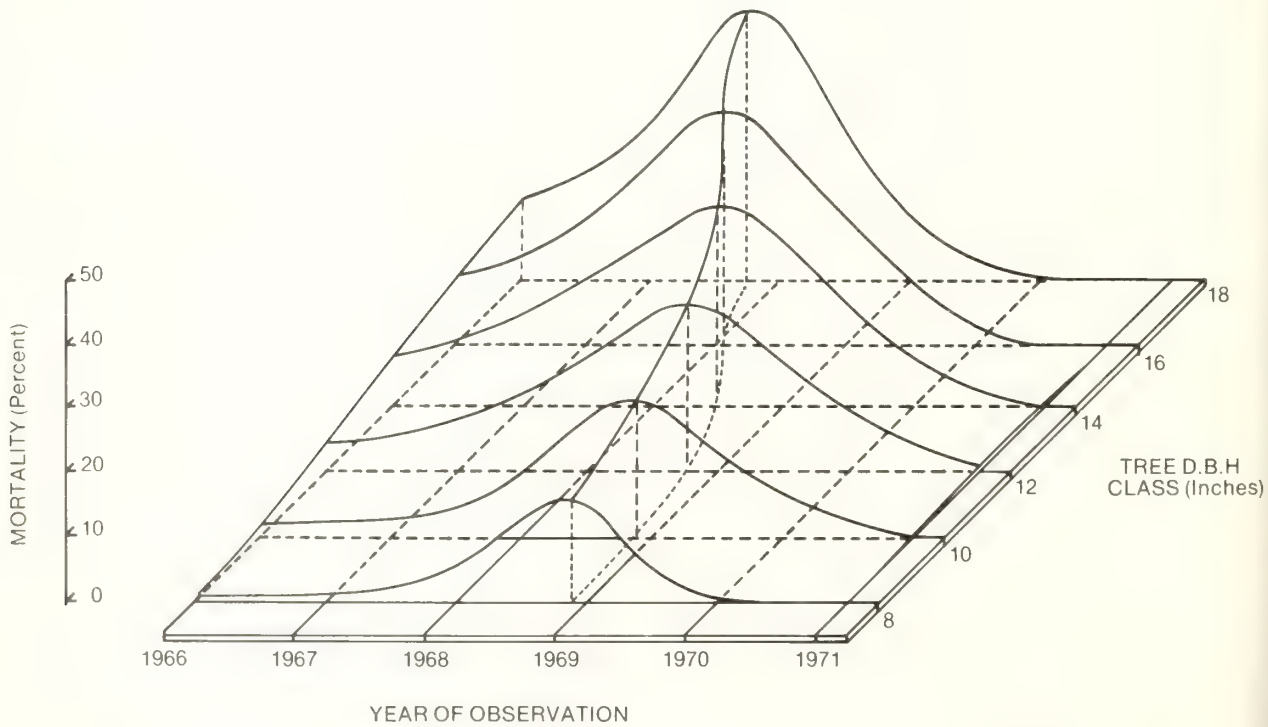
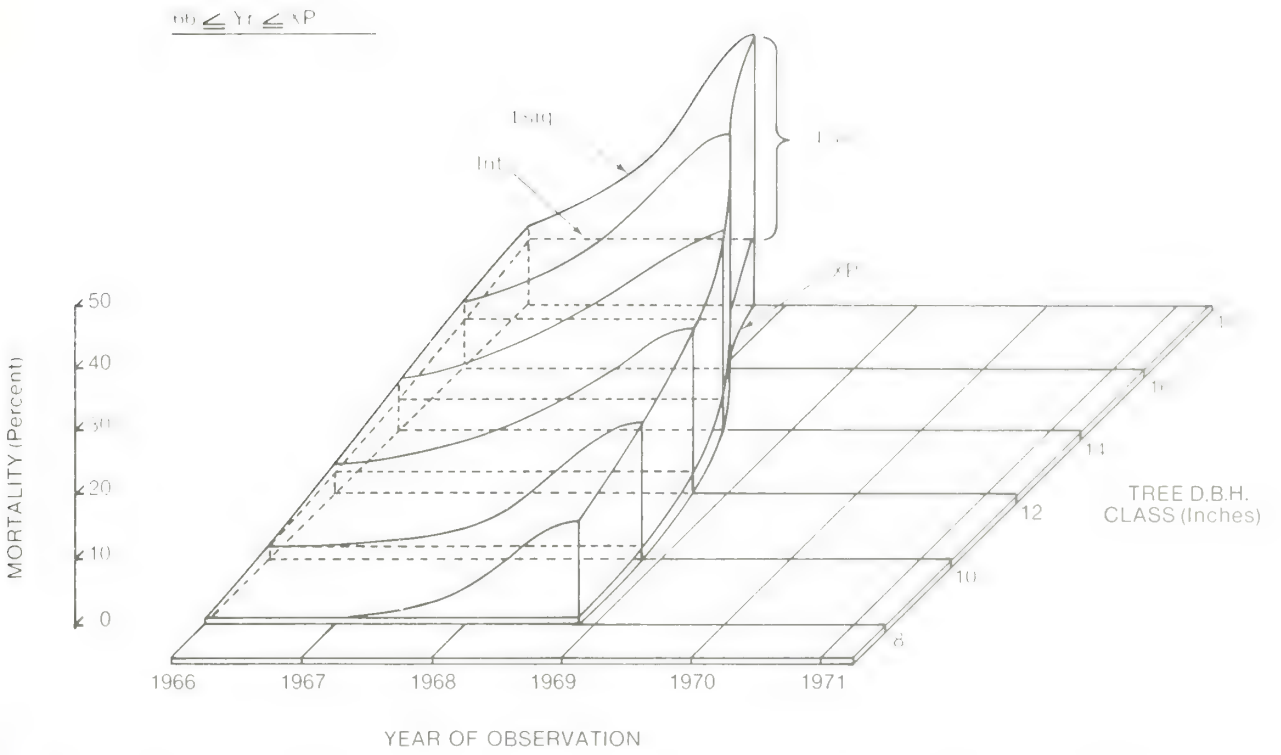
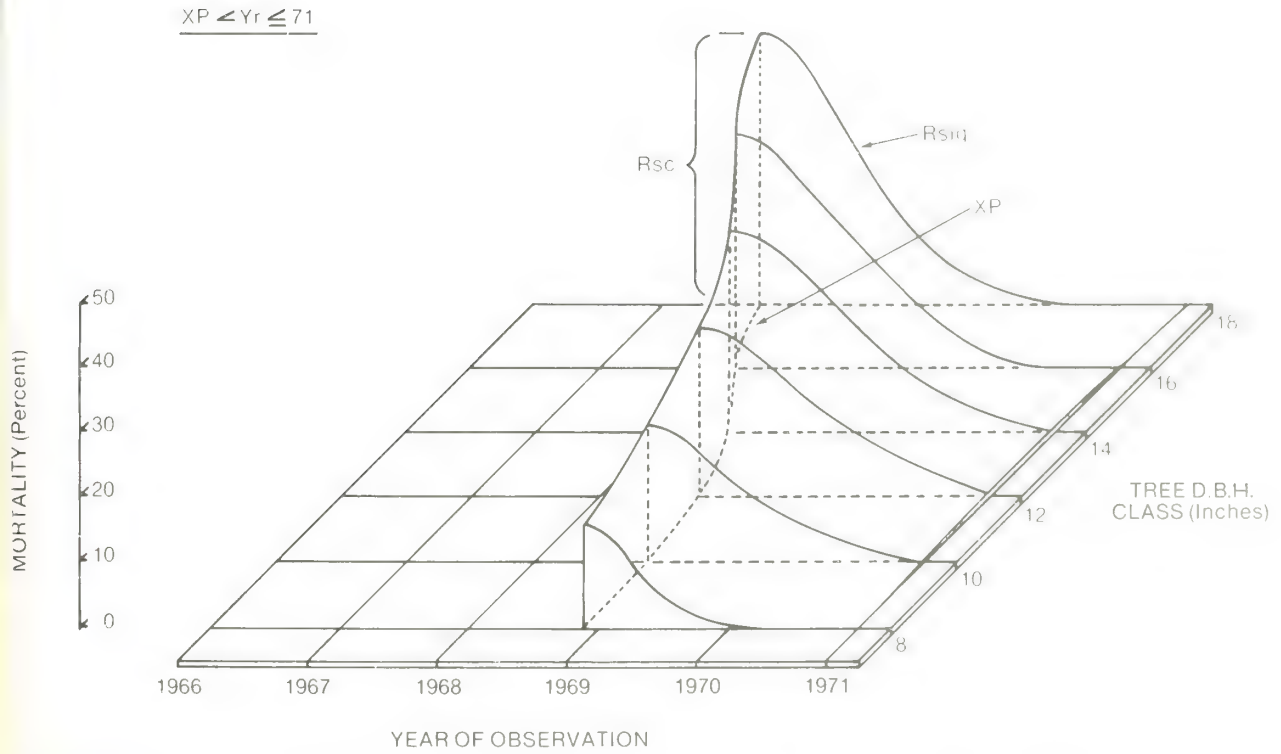


Figure 1.--Tree mortality over the course of a beetle epidemic.


66 ≤ Yr ≤ XP
Rsiq
Int
Rsc
XP
50
40
30
20
10
0
MORTALITY (Percent)
1966
1967
1968
1969
1970
1971
YEAR OF OBSERVATION
12
10
8
TREE D.B.H.
CLASS (Inches)


XP ≤ Yr ≤ 71
Rsc
Rsiq
XP
50
40
30
20
10
0
MORTALITY (Percent)
1966
1967
1968
1969
1970
1971
YEAR OF OBSERVATION
18
16
14
12
10
8
TREE D.B.H.
CLASS (Inches)

Sigmoids are described within the range XP ± 5 years (yr), since all sigmoids are estimated to be fully expressed therein. Use of a constant maximum range, such as XP ± 5 years, keeps descriptor components to a minimum for the sigmoidal time effects, yet permits satisfactory matching of the objective curves in this case. Restated in general terms, the whole descriptor is as follows:

Mortality percent = Int + Lsc (Lsig) + Rsc (Rsig)

where

Lsig = left sigmoid = f_L(Ln, LI, XP, Yr)...see the basic sigmoid parameters defined in Matchăcurve-1, page 3.

Ln = Lsig power = f_1(d.b.h.)

LI = Lsig inflection point as a proportion of the range in years from XP-5 to XP, = f_2(d.b.h.)

XP = point in time where surface peaks = f_3(d.b.h.)

Rsig = right sigmoid = f_R(Rn, RI, XP, Yr)

Rn = Rsig power = f_4(d.b.h.)

RI = Rsig inflection point as a proportion of the range in years from XP+5 to XP, = f_5(d.b.h.)

Int = intercept, left edge = f_6(d.b.h.)

Rsc = Rsig scalar = ridgetop = f_7(d.b.h.)

Lsc = Lsig scalar = ridgetop-Int

Segmental constraints:

Left side; $66 \leq Yr \leq XP$, discrete values only

Right side; $XP < Yr \leq 71$, discrete values only

Either side; $8 \leq$ d.b.h. ≤ 18, midpoints of 2-inch d.b.h. classes only...8, 10, 12, etc.

The model, refitted by least squares to smoothed mortality percent at 36 control points on the original data cross-sections over time resulted in an R^2 of 0.96. Used as a goodness-of-fit index, this high R^2 value attests to the fact that the descriptor duplicates the objective graph with reasonable accuracy.

EXAMPLE 2
AN ASYMMETRICAL, BELL-SHAPED RIDGE: THREE SEGMENTS

Quality score (t) was originally described (fig. 1) as an aggregate of [illegible] regions over flow (F) and stability (S) of gap-graded road materials, a strongly segmented descriptor (Lee, and others 1973, fig. 14). The objective here was to *smooth* the figure and *minimize* the number of segments in the descriptor. Although the problem is an unusual one, its solution serves admirably to demonstrate descriptor segmentation.

From figure 4, it can be seen that opposite sides of the ridge differ substantially in slope so that an asymmetrical, flat-topped, bell-shaped curve would be required to describe the cross-section at any point in S while rounding the junctures of planes. A relatively simple descriptor alternative involves segmentation of the (S,F)-regions as shown, with left and right orientation lines. Note that the lines are parallel to their respective sides of the ridge and lie one unit in F closer to the ridge center. This permits use of a single, but different, sigmoid cross section to represent and smooth the corners of each segment, left and right. The sigmoids will peak at their respective orientation lines and will be functional over a constant distance from them (left or right as appropriate). The constant will vary by side as needed. Since the ridge is flat-topped, it will have a value of t = 10 everywhere in the center segment.

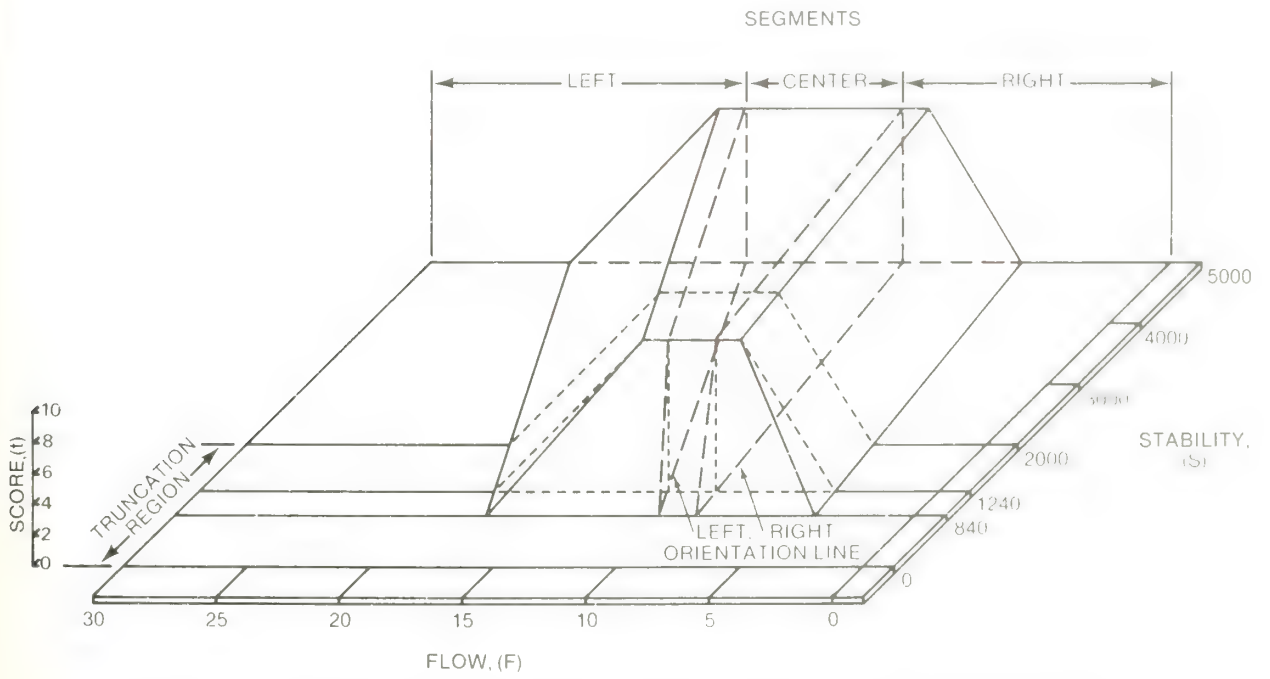


Figure 4.--Quality of gap-graded road materials: segmented planar form.

Then, to this point, we have described a ridge with three segments specified in terms of S and F: the sigmoidal effect to the left of the left orientation line; the sigmoidal effect to the right of the right orientation line; and the flat ridge area between these lines at a value of t = 10.

Finally, a sigmoidal truncation of the front end of this ridge is achieved through multiplication of all components of the descriptor by an appropriate sigmoid, changing in value from zero to one within the range $0 \leq S \leq 2000$, and being applicable for $0 \leq S \leq 5000$.

In general terms, we have:

Lsig and Rsig = left- and right-segment sigmoids, respectively

LO, RO = left- and right-orientation lines, respectively

CC = center segment, constant

Tsig = truncator sigmoid

Then

$$t = Tsig\ (Lsig + CC + Rsig)$$

and

$$Tsig = f(S)$$

$$Lsig = f(LO,F)$$

$$Rsig = f(RO,F)$$

$$LO = f(S)$$

$$RO = f(S)$$

Limits

For Lsig, $LO < F \leq 28$

For Rsig, $0 \leq F < RO$

For CC, $LO \leq F \leq RO$

and, $0 \leq S \leq 5000$

The final descriptor form is shown in figure 5 along with the original planar form for comparison. It can be *seen* that the descriptor does a creditable job of emulating the planar form while smoothing the corners, all with 3 segments in place of the original 11 segments.

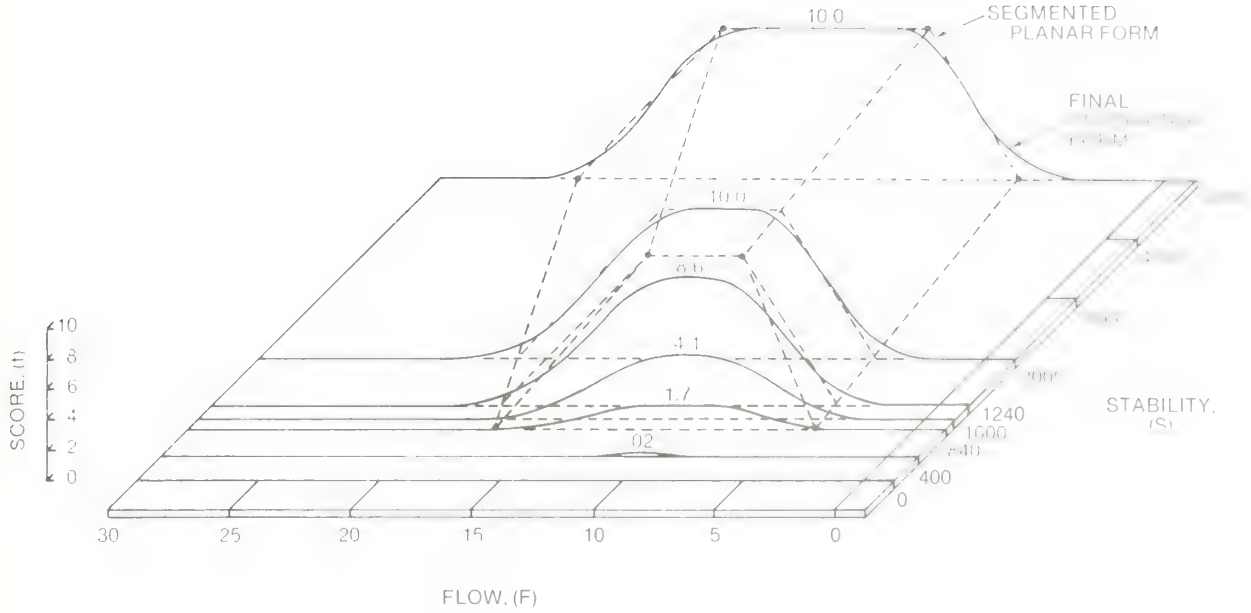


Figure 5.--Quality of gap-graded road materials: segmented planar and final descriptor forms.

APPENDIX

Example 1: Specific Mathematical Descriptor

Mort. percent = k(Int + Lsc[Lsig] + Rsc[Rsig])

where

k = least squares coefficient = 0.9877

$$Int = 1 + 0.2521\ (d.b.h. - 8)^{1.69}$$

$$Rsc = 2.6429\ (d.b.h.) - 5.157$$

$$Isc = Rsc - Int$$

$$Lsig = \left\{ \frac{e^{-\left|\frac{5 - Yr - XP}{\frac{5}{1 - LI}} - 1\right|^{Ln}} - e^{-\left(\frac{1}{1 - LI}\right)^{Ln}}}{1 - e^{-\left(\frac{1}{1 - LI}\right)^{Ln}}} \right\}$$

$$XP = 67.65 + 1.2257\ e^{-\left|\frac{20 - d.b.h.}{\frac{12}{0.65}} - 1\right|^{3.9}}$$

$$LI = 0.851 - 0.1531\ e^{-\left|\frac{7 - d.b.h. - 13.5}{\frac{7}{0.45}} - 1\right|^{4}}$$

Ln = 1.5

Rsig = as for Lsig using RI and Rn

$$RI = 0.752 + 7.8173 \times 10^{-4}\ d.b.h. - 14.8$$

Rn = 2

Limits

$66 \leq Yr \leq 71$, discrete units only

$66 \leq Yr \leq XP$, for Int, Lsc, Lsig

$XP < Yr \leq 71$, for Rsc, Rsig

$8 \leq d.b.h. \leq 18$

SUPPLEMENTARY EXPLANATORY DETAIL FOR EXAMPLE 1

Int was estimated from leftward extension, from the ridge, of the mortality trend indicated by data in each of six 2-inch d.b.h. groups. All six trends reached lower asymptotes by 1963 and at that point suggested a flat, concave-upward curve over d.b.h. (fig. 6). This was satisfactorily described using Matchacurve-2, set A-1.

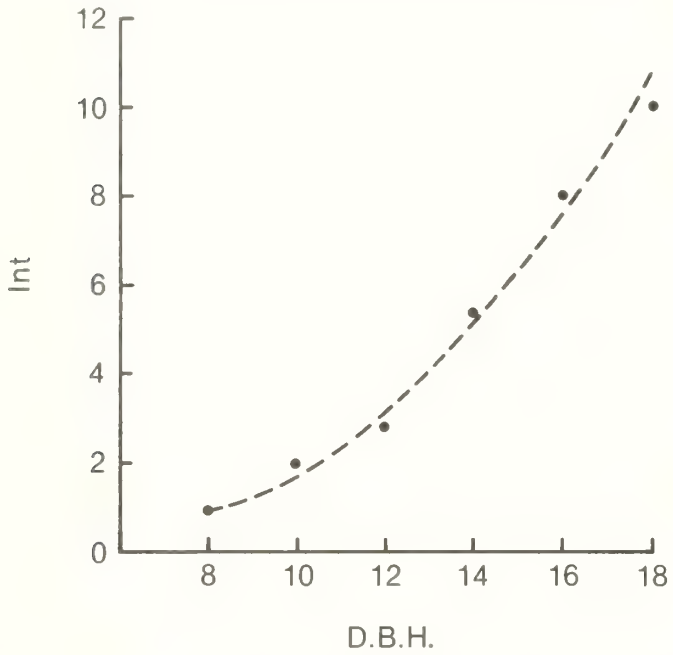


Figure 6

Rsc is simply the height of the ridge above zero and serves as the scalar for the right-half sigmoids. Rsc is a linear function of d.b.h., adopted to represent the somewhat irregular pattern of ridge values for the six d.b.h. groups (fig. 7). Note that the ridge line in figure 1 only *appears* to be sigmoidal by reason of the sigmoidal change of point-of-peaking in time, with a change in diameter.

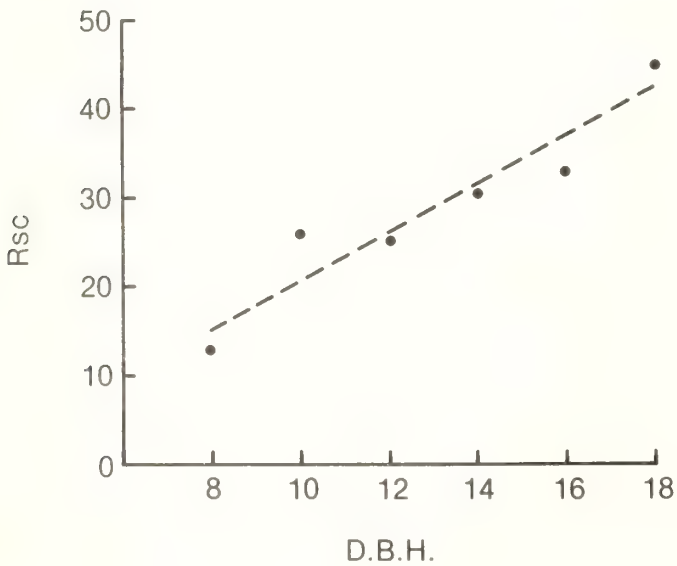
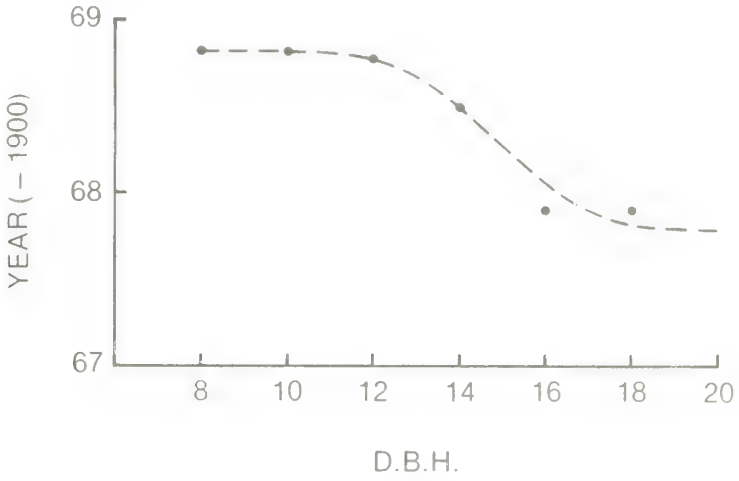
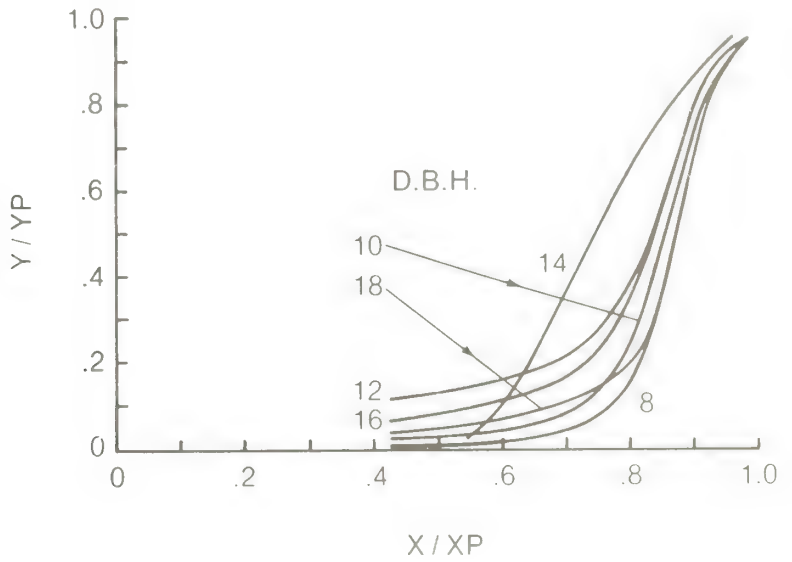


Figure 7

, the point in time at which the bell-shaped curve peaks, [illegible] the XP's for the six data-group cross-sections (fig. 8). This curve was estimated to asymptote at 68.88 and 67.75. A suitable match was found in the sigmoids of Matchacurve-1 when the d.b.h. was reversed; namely, transformed to 20-(d.b.h.).



Lsig specifies the sigmoidal shape of the left side. After transforming Year to 5-|YR-XP|, to create X-values ranging from zero at XP-5, to 5 at XP, the six d.b.h.-group cross-sections (left halves) were each scaled to 1.0 in X and Y...at critical points in X. Overlay curves (see Matchacurve-1) were plotted for these cross-sections (fig. 9). The pattern was one of wider curve crowns near d.b.h. = 14 inches, narrowing with increasing departure from that d.b.h. This is reflected in the bell-shaped function for the inflection points, LI. Also, Matchacurve-1 Standards with n = 1.5 were found to represent this curve array with reasonable accuracy, so Ln was set at the constant, 1.5.



LI, the function for the inflection points, is the dashed line in figure 10, and represents the inflection points adopted and plotted for each overlay curve. LI reflects the width-of-curve-crown trend noted under Lsig and in the text.

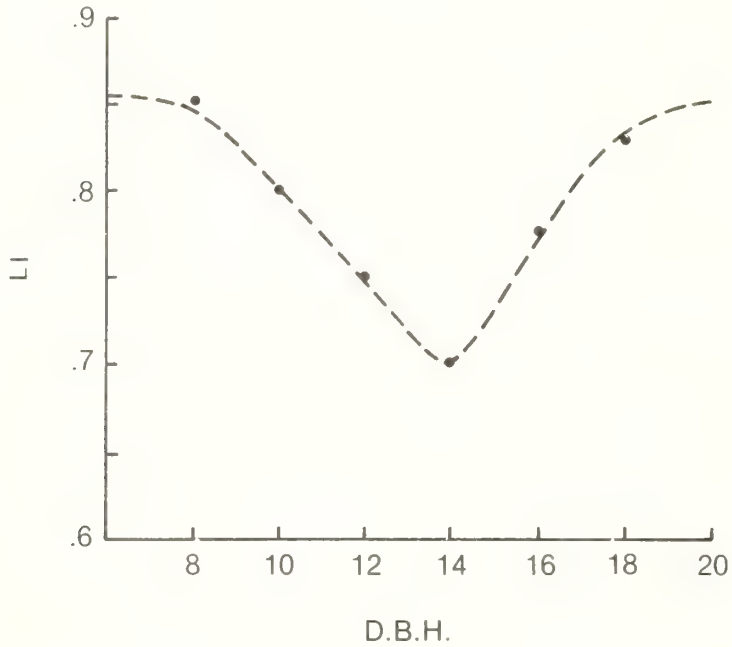


Figure 10

Rsig, RI, and Rn were obtained in a similar fashion. The Year transform again was 5-|Yr-XP| and ranged in value from 5.0 at XP to zero at XP + 5. The right-side cross-sections were fairly well matched by Standards with n = 2, so Rn = 2. RI showed the same general widening of curve crown at d.b.h. = 14 inches.

Example 2: Specific Mathematical Descriptor

If

$F > LO$, $t = Tsig(Lsig)$

$LO < F < RO$, $t = 10(Tsig)$

$F < RO$, $t = Tsig(Rsig)$

where

F = soil flow

$LO = 8.586 + 0.0017036(S)$

$RO = 8.404 + 0.00048076(S)$

S = soil stability

$$Lsig = 10\, e^{-\left|\frac{\frac{(LO + 20 - F)}{20} - 1}{0.23}\right|^{\cdots}}$$

$$Tsig = 1 - e^{-\left|\frac{\frac{(6000 - S)}{6000} - 1}{0.185}\right|^{6}}$$

$$Rsig = 10\, e^{\left|\frac{\frac{RO - 11 + F}{11} - 1}{0.30}\right|^{2.4}}$$

Limits

$0 \leq F \leq 28$

$0 \leq S \leq 5000$

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Methods are shown for achieving sensitivity in mathematically describing asymmetric curve forms. Independent, but compatible, descriptors are developed for each of several response surface regions or segments, in the examples given. The methods are analogous for problems necessitating the use of additional segments and or dimensions.

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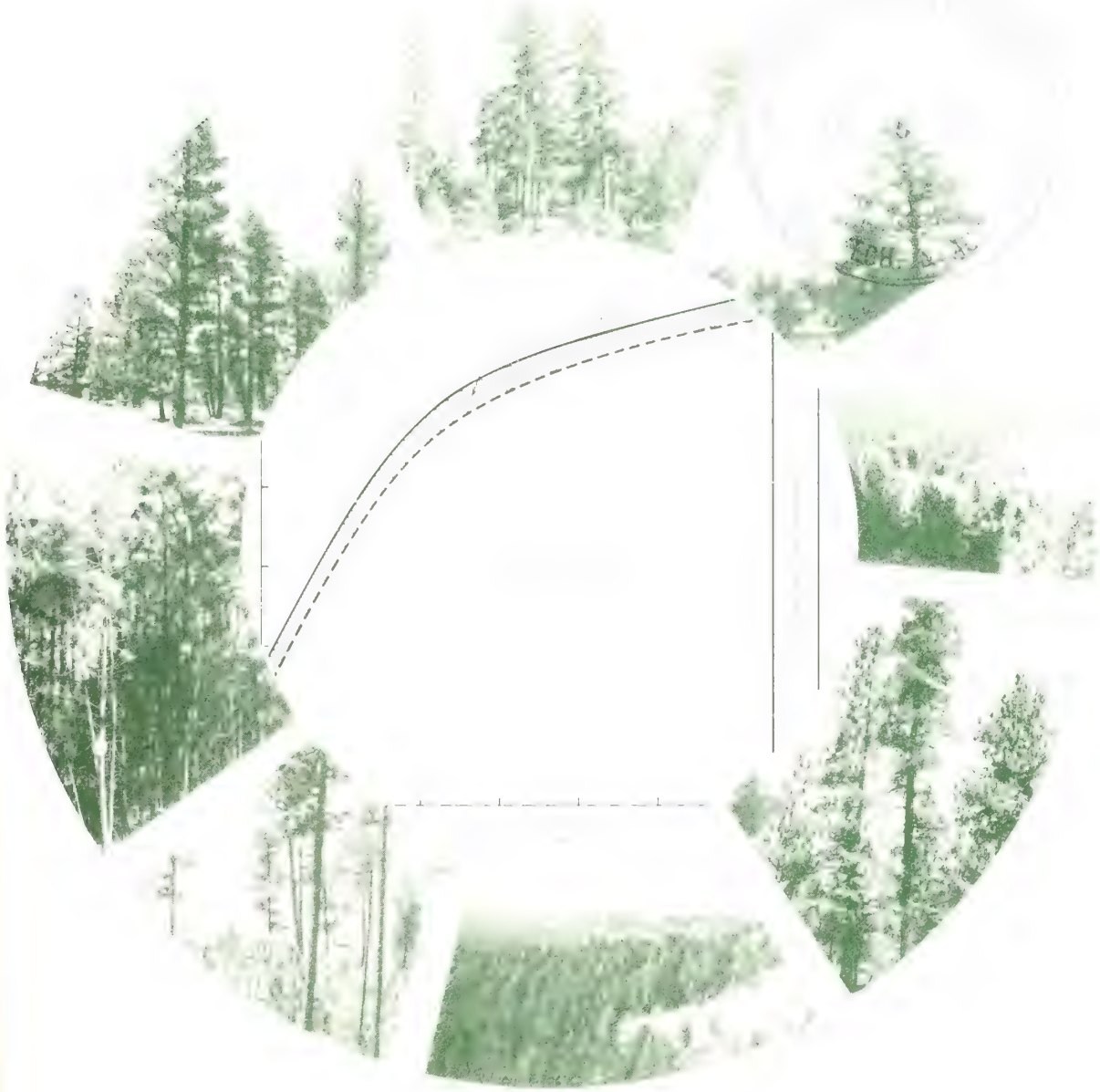

ASSESSING THE TIMBER RESOURCE SITUATION ON A WORKING CIRCLE USING INVENTORY DATA

Alan W. Green

USDA Forest Service Research Paper INT-183
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

PREFACE

This publication is designed so that the reader with limited time can quickly obtain a summary of the complete paper by reading the highlights in the page margins and selected portions of the text.

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1975

ASSESSING THE TIMBER RESOURCE SITUATION ON A WORKING CIRCLE USING INVENTORY DATA

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ABSTRACT

Realistic projections of timber supplies require knowledge about the land's wood-growing capacity, constraints on the use of forest land for timber production, and the extent and condition of the existing timber resource. Timber inventory data can be used to estimate potential available output and to assess the existing resource in terms of general management needs and of its performance in producing usable wood.

INTRODUCTION

An expanded program of intensive timber management is one way to increase wood supplies from a shrinking commercial forest land base. But, proposals to increase funding for an accelerated management program on National Forests are now being met with the question, "How much (more) wood will be produced with the money requested?"

There is considerable difference between the level of output it is possible to achieve and the level of output that might be economically desirable, considering the need for and the value of nontimber uses of the forest land and the condition and nature of the timber resource at hand. To answer the question then, the manager must have some information about (1) the productivity of the land, (2) the costs of management activities, (3) the impact of nontimber uses on availability of wood for harvest, and (4) the nature of the timber resource he has to work with.

The first three kinds of information enable the manager to estimate the sustainable output from his working circle under a fully managed or "regulated" condition. However, the actual near-future output will be determined by the character of his existing timber resource and the harvesting schedule used during the conversion period, after which the forest will be fully regulated.

Presently, harvesting schedules for National Forests are receiving a lot of attention. At issue is the Forest Service policy aimed at achieving a sustained and nondeclining even flow of timber from National Forest lands. This necessitates a somewhat longer time for liquidating old-growth stands than critics of the policy think is wise. A more rapid rate of old-growth liquidation could well result in a future "fall down," or drop, in sustainable output, which the Forest Service policy is designed to avoid. On the other hand, a greatly accelerated management program could increase total wood growth on a working circle and allow a more rapid cut of old-growth volume without a substantial future drop in sustainable output.

Many computerized models are used for determining the "best" harvesting schedules. All are based on some specific assumptions about factors such as present and prospective growth rates, volumes, and liquidation rates. Moreover, the assumptions used operate within and reflect the constraints set by basic policy objectives.

It is not the purpose of this paper to look at the propriety of any harvest scheduling scheme. Any such scheme is designed to offer the best chance to achieve the goal it is to serve. But, before assumptions are developed for use in generating a harvesting schedule, the manager should have some basic information about the biological possibilities for wood output, associated costs, and the nature of the resource stock he has to work with. Unless there is first a biological assessment of the resource situation, there is no foundation for a meaningful economic analysis for management planning purposes.

The data now being collected in timber inventories can be used to pinpoint problems the manager must deal with on the ground and in planning the management of the forest resource. Past efforts using inventory data for such purposes have been somewhat neglected.

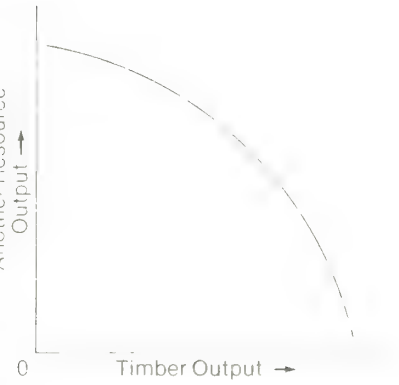
This paper discusses an approach, using timber inventory data, for looking at the biological side of timber production possibilities. It (1) demonstrates estimation of potential wood output in relation to nontimber-use demands on the forest land and management costs, and (2) discusses ways of identifying some problems and opportunities that must be dealt with in developing a harvest schedule and long-range management plan for eventually achieving that potential.

Data used are from the recently completed timber inventory of the Sitgreaves Working Circle, Apache-Sitgreaves National Forest in Arizona. The sampling scheme used was a stratified double sample (photo and field) with a random start, using a cluster of 10 sample points at each field location. Because ponderosa pine and Douglas-fir make up all but 1.3 percent of the commercial forest land and account for virtually all timber output from the working circle, only land occupied by these species or capable of growing them is considered in estimating potential output.

During the several years since the inventory data were compiled there have been some changes in land classification and attendant area, volume, and growth data. Therefore, basic data shown here should not be considered to be current official land and timber statistics for the Sitgreaves Working Circle. These data should be used only to follow the evaluation procedures.

THE APPROACH

Some Basics



■ JOINT PRODUCTION AND USE OF FOREST RESOURCES. If the objectives of growing and managing timber on forest land are to be met, timber cannot be looked at in isolation. Some amounts of other resources are jointly produced or available with it and, presumably, some nontimber uses of forest land are necessary to meet those objectives.

Maximizing the output of timber will almost certainly result in less than maximum output of some other resources possible on the same land. Therefore, some knowledge of the trade-offs between timber and other possible resource outputs is necessary for planning the management of the timber resource that will hopefully produce the desired output of timber and associated renewable resources.

■ QUESTIONS TO BE ANSWERED. A timber inventory and analysis should be designed to answer some basic questions:

WHAT COULD BE?

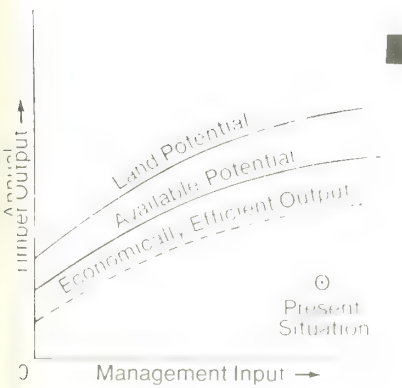
WHAT IS?

WHAT SHOULD BE?

1. How much wood is it possible to produce on a commercial forest land base?
2. What is the current rate of wood production from this land?
3. What must be done to achieve the potential?
4. What are the relationships between timber production and other uses and values produced?

Answers to the first two questions provide the foundation for estimating the realistic future timber supplies available from the forest unit. Answers to questions 3 and 4 help define the future management strategies that will lead to achieving the target output.

The Nature of the Analysis



■ PRODUCTION POSSIBILITIES. The thrust of the approach described here is to estimate the realistic potential timber output and to assess the problems and opportunities associated with achieving that potential.

Factors to be considered include the productive capacity of the land, constraints on timber management and harvesting activities, management costs, and the extent, nature, condition, and current performance of the existing resource with which the manager has to work. Defining economically efficient output is beyond the intent of this paper.

Determinants of Timber Output

■ THREE BASIC FACTORS. The potential realizable output of timber is influenced primarily by:

- o Productivity of the land
- o Availability for harvest of the wood produced
- o The extent and effectiveness of management activities

□ LAND PRODUCTIVITY. Productivity classes assigned to commercial forest land indicate the quantity of wood (cubic feet per acre per year) fully stocked natural stands of a given species could produce. The terms yield-capability class, productive capacity, and site class have the same meaning.

Mean annual increment for natural stands could be maintained or exceeded through intensive management.

Productivity-class designation is keyed to the growth rate at culmination of mean annual increment in fully stocked stands and sets the upper limit of potential output from a given site under intensive management. Not considered are such management activities as fertilization or use of genetically superior strains of particular species.

Site conditions can influence the number of trees it is possible to grow and therefore, the quantity of wood that can be grown.

Site-index values computed from site-tree data, yield estimates from normal-yield tables, and other data relating to productivity are used to estimate potential yield capability. Such yield estimates may or may not accurately reflect the true productivity of the land at any given location. A low stocking level at a location can result in a computed mean annual increment of less than the 20 cubic feet per acre per year required for a productive forest land classification. Therefore, information on factors affecting the stockability of the specific location is used to more accurately assign a productivity rating for that site. If the conditions of site and stand uniformity set by the developers of site-index curves and yield tables are not met, then logically some discounting or reduction of the potential yield estimate should be made for the location.

Exposed bedrock, heavy clay soils, areas of severe erosion, and washes and arroyos, for example, can prohibit the establishment and growth of commercial tree species. But some understocked stands have the capability to grow commercial species, and the productive potential is greater than what is currently evident on the site.

The point is, the basic normal-yield estimates must be adjusted to accurately reflect productivity.

Not all the wood produced will be available.

□ AVAILABILITY. In the definition of commercial forest land, emphasis is on the land being both suitable and available for the production and harvest of wood products. Unfortunately, while land may be suitable and available for growing wood, some wood grown might not be available for use.

Without additional investment in roads, lack of access to otherwise usable timber [illegible] or, if accessibility is no problem, multiple use, environmental, technological, and legal considerations result in constraints on the amount of wood that can be removed from certain areas. Such constraints can also increase the costs of management and harvesting activities.

Management costs money...

and costs for the same activity can differ because of varying conditions at the worksite.

□ MANAGEMENT LEVELS. Management levels are important in developing estimates of potential timber output because of the costs associated with management activities. Costs for the same activity can differ because of the varying circumstances under which it is done. Planting may cost more on poor sites than on good sites; thinning in natural stands may cost more on good sites than on poor ones because of the number of trees to be removed.

Available management money also affects the speed with which managers can reach the unit's potential output. Aside from liquidating or depleting growing stock, there are basically four ways in which timber output can be increased:

Management measures must be the right kind...

1. Shorten the regeneration period.
2. Increase growth rates. (Specific activities such as fertilization, use of genetically superior planting stock, and precommercial and commercial thinning fall into the general category of increasing growth rates.)
3. Reduce losses from insects, disease, and fire.
4. Improve utilization.

and be applied at the right time.

The manager is somewhat limited in his opportunities to apply techniques of management toward any of these four basic vehicles. Regeneration activities apply to nonstocked areas and to new areas as they are cut. Thinning is a live option only to the extent there are overstocked stands.

In working toward achievement of the output potential, the manager has only his existing timber resource; it is all he has to work with. The basic inventory data provide the manager with information about the condition of the timber resource and problem situations he must deal with in planning his management strategies.

The manager needs to know the situations to be dealt with to increase output.

Gross and net volume growth, mortality, diameter distribution, stocking levels, and other parameters that relate to the general management options can serve as signals, calling attention to situations needing some remedy before the potential output can be reached. In addition, information about certain attributes of the forest can help explain the existence of undesirable situations and often indicates an appropriate remedy.

ESTIMATING THE POTENTIAL OUTPUT

The Least Cost Path to Potential

Land plus management input minus constraints equals potential available output.

■ DEVELOPING AN OUTPUT CURVE. It is important to remember that this part of evaluating timber-production potential relates only to what the land could produce, given certain amounts of dollars for management activities and whatever management and land-use constraints are in force. How much wood might be harvested over a specified period if, beginning with bare land and a seed source, certain management activities were undertaken?

Potential output curve is neither a production curve nor a supply curve.

An output curve traces the eventual production at a number of management levels, once the forest unit is in a fully regulated condition. It does not define the most economically desirable budget level, which requires assigning per unit values of output.

There are many ways to develop an output curve. Computers offer a speedy method for summarizing pertinent information and, in some cases, for actually computing and even plotting the marginal cost-marginal output information that is the foundation of the curve.

Land classes reflect impacts on wood availability and on the the costs to produce it.

□ LAND CLASSES. The commercial forest land of the working circle inventoried was categorized into three land classes:

Standard.--Land available and operable now. No nontimber-use impacts affecting the growing costs or expected yields of timber.

Special.--Land available and operable now, but with ecological or other use constraints affecting the cost of growing timber, expected yield, or both.

Marginal.--Land potentially available and operable, or both, but not now scheduled for harvest because of excessive development costs, low product returns, or resource protection constraints.

Availability classes define the amount of impact on wood yields or on removals possible.

□ AVAILABILITY CLASSES. An availability class was designated for each of the various kinds of land included in each land class (table 1). Because the commercial forest land on the working circle is virtually all roaded, availability is a matter of constraints on removals related to the values of nontimber use. Using Standard Land as Availability Class I where full yields can be expected to be captured, other availability classes were defined in terms of the proportion (percent) of Standard Land yields expected, considering impacts of other uses. A total of five availability classes were recognized (tables 1 and 2).

Table 1 -

Land class	Availability class	Percent of standard land yield expected	Land condition
Standard	I	100	All [illegible]
Special	I	100	[illegible]
	II	90	[illegible]
	III	10	[illegible]
	IV	0	[illegible]
Marginal	I	100	[illegible]
	V	50	[illegible]

Land recently acquired by the Forest, but without [illegible] until [illegible] 1999.

Presently unavailable with current [illegible]

Table [illegible]

Availability class	Productivity class	Standard	Special	Marginal	Total
I	20-35	76,[illegible]	1,[illegible]	19,[illegible]	[illegible]
	36-50	58,[illegible]	[illegible]	4,553	65,207
	50+	19,145	14	2,047	[illegible]
Total		353,770	1,574	25,729	[illegible]
II	20-35	0	10,228	0	10,228
	36-50	0	2,447	0	[illegible]
	50+	0	459	0	[illegible]
Total		0	13,134	0	[illegible]
III	20-35	0	[illegible]	0	15,564
	36-50	0	5,095	0	[illegible]
	50+	0	1,095	0	[illegible]
Total		0	[illegible]	0	[illegible]
IV	20-35	0	13,732	0	13,732
	36-50	0	2,216	0	[illegible]
	50+	0	[illegible]	0	[illegible]
Total		0	[illegible]	0	[illegible]
V	[illegible]	0	0	[illegible]	[illegible]
	36-50	0	0	[illegible]	535
	50+	0	0	215	215
Total		0	0	5,145	5,145
Total		353,770	51,044	28,874	[illegible]

Marginal Land is separated into inoperable and steep slope areas, both presently unavailable with current logging techniques and prudent operation. However, in the event that balloon or helicopter logging should be introduced, the inoperable area could be fully utilized. Therefore, that area was put into Availability Class I to compute a potential yield. Management costs would be considerably higher for the area, of course.

Availability Class V consists of steep slope land that could not withstand full harvest and management activity even with aerial logging. It is estimated that only about 50 percent of the volume grown could be captured without irreparable damage to the resource (table 1).

Four general levels of management were used to estimate potential output...

□ MANAGEMENT LEVELS. Four levels of management were used in estimating wood production. Those considered can be defined in terms of regeneration effort and stocking control:

Management level	Regeneration effort	Stocking control
1	NO	NO
2	NO	YES
3	YES	NO
4	YES	YES

Obviously, one always has the choice of doing nothing following harvesting of mature timber. Beyond that, one can shorten the regeneration period or shorten the precommercial growing period by some activities or combination of activities, and thereby increase the total yield over some specified time frame.

Regeneration effort in Management Level 3 indicates natural regeneration with site-preparation work in addition to routine logging disturbance and for which some cost would be incurred. In Management Level 4, partial or complete planting of the cutover area is indicated.

but more could be used.

Stocking control indicates only precommercial thinning at some cost; however, it is assumed that if precommercial thinning were done, commercial thinning would also be undertaken.

Cost and yield estimates associated with different management levels are needed for each

□ COST AND YIELD ESTIMATES. Basic cost and yield estimates required to approximate the potential output curve are illustrated in appendix tables 12, 13, and 14. Many formats could be used to display such data; however, because this study was limited primarily to two species under common

land class and availability class.

management regimes, the intensive management is applied by land class only. Where [illegible] and user needs [illegible] standard land. [illegible] descriptive features is at this point unnecessary because we are [illegible] constraints on removals.

The inventory was designed to separate four productivity classes. However, examination of the data showed most of the land fell into the 20 to 50 cubic foot per acre per year category, a situation that would not allow any meaningful evaluation of management levels by site quality. Even by splitting the 20 to 50 cubic foot productivity class, nearly 80 percent of the Standard Land is low site (20 to 35 cubic feet per acre per year). The number and magnitude of productivity classes appropriate for such evaluations will naturally vary in relation to the character of the forest land under study.

Use the best data available to make the estimates.

The best information available for the working circle inventoried indicated that the average productivity of the 20 to 35 cubic foot class probably was about 33 cubic feet per acre per year. Averages for the other classes were assigned on the basis of site-index data converted to a productivity rating in cubic feet. It appears likely that productivity of forest land on the working circle inventoried was somewhat understated as a result of the manner in which some of the inventory data were collected. Because the data are used for illustration purposes only, this does not detract from the methods described. However, the importance of reliable land productivity data cannot be overemphasized.

The on-site treatment costs were developed from average costs experienced by the Forest over the past several years; all overhead is excluded. An adjustment was made for inflation and some best estimates were made of increased management costs for areas, such as travel and water influence zones and backdrop and scenic areas, where virtually all traces of forest management activities probably would have to be erased.

The cost figures in columns 13 and 14 in appendix tables 12, 13, and 14 are important for the final calculations of output curve data; they are the basis for ranking the timber production opportunities by cost per unit to develop cost-output information that will provide the foundation for defining the output curve.

The cost per acre per year for management, and the expected yields per acre per year were used to develop table 3 and appendix tables 15 and 16. Cost per unit is converted to cost

per thousand cubic feet for convenience and clarity, and a ranking is made (col. 8, table 3 and appendix tables 15 and 16) of the management options in terms of cost per thousand cubic feet of wood produced.

Table 3.--*Area and expected costs and yields by productivity class*[1]

STANDARD LAND

Productivity class (ft^3/acre/yr)	Acres (1)	Mgt. level (2)	Annual mgt. cost per acre (3)	Annual yield per acre (4)	Management cost per year (3)x(1) (5)	Yield expected per year: (4)x(1): (6)	Cost per: M cubic feet: (5): (6): (7)	Rank (8)
			$	ft^3	$	ft^3	$	
20-35	276,245	1	0	19.2	0	5,303,904	0	1
		2	0.21	26.8	58,011	7,403,366	7.84	6
A		3	.21	24.2	58,012	6,685,129	8.68	8
		4	.96	33.0	265,195	9,116,085	29.09	10
36-50	58,382	1	0	35.4	0	2,066,723	0	1
		2	.29	43.1	16,931	2,516,264	6.73	5
B		3	.11	38.8	6,422	2,265,222	2.84	3
		4	.82	48.0	47,873	2,802,336	17.08	9
50+	19,143	1	0	48.2	0	922,693	0	1
		2	.38	61.1	7,274	1,169,637	6.22	4
C		3	.06	50.4	1,149	964,807	1.19	2
		4	.52	65.0	9,954	1,244,295	8.00	7
Total	353,770							

[1]The same information for Special and Marginal Lands is found in appendix tables 15 and 16.

Lettered productivity class designations (A, B, and C) are shown so they maybe related to similar designations used in computing the information for the 64 management combinations (table 4).

The manager can do nothing, or something...

but he can do only one level of management at a time on the same land.

□ COSTS AND YIELDS. Several points need to be made about developing the cost-output values. First of all, it is obvious that if nothing is done, after harvest, wood will be produced anyway. It will cost nothing but time and worry.

Secondly, only one level of management can be undertaken on land of a given productivity class at one time. To build the output curve then, the beginning point is the expected yield available at no cost. By summing the expected yields from Management Level 1 in each land-productivity class and availability class for Standard and Special Land (appendix

tables 15 and 16), the annual output with no management cost is found. To increase output, expenditures for management are required.

□ AN APPROXIMATE CURVE. A reasonable approximation of the output curve for Standard Land can be made by assuming that all acres in a productivity class will be managed at the same level and successively adding in the next most cost-effective opportunity as indicated by the ranking in column 8, table 3. As this is done, however, the management level previously used in the productivity class must be removed as the new one is included. The marginal costs and yields of the new option over the previous one are calculated. When all nine options to spend money have been used, the marginal costs and yields are cumulatively summed and the points plotted. This method results in a curve accurate at both ends, but too low in the middle.

The output curve is built on the marginal output and costs for successively more expensive management undertakings.

A more accurate curve requires that all possible combinations of options be ranked and marginal costs and output computed. On Standard Land, for example, there are four management levels for each of three productivity classes (sets). Because three management options must be used at a time, one in each productivity class, there are 64 combinations to consider. The number of combinations is:

$$\left[\frac{n!}{r!(n-r)!}\right]^{k}$$

where

n is the number of management levels (in a set)
r is the number to be taken at a time
k is the number of productivity classes (or sets).

A small computer program for listing all possible combinations and computing the costs and yields saves many hours (table 4).

Several computerized resource allocation models are now in use that spell out directly the most desirable timber output level over the next 10 to 12 decades. The output levels indicated are desirable only in relation to the criterion of goodness used to make the decision, however. There are many assumptions about values of timber, other associated resources, or both, in such models that are open to question for any particular stand or working circle to which they are applied.

It would seem to be premature to define "desirable" output and to use it as a production target without knowing first what is possible and the condition of the resource in terms of the likelihood of achieving it in the near future.

class	Treatment costs			Annual yield				
				Productivity class				
			Total	A	B	C	Total	Cost M tt
	0	0		5,303,904	2,066,723	922,693	8,293,319	
		274	7,274	5,303,904	2,066,723	1,169,637	8,540,264	
	0	1,149	1,149	5,303,904	2,066,723	964,807	8,335,434	
		9,954	9,954	5,303,904	2,066,723	1,244,295	8,614,922	
	,931	0	16,931	5,303,904	2,516,264	,693	8,742,	
	16,931	274	4,205	5,303,904	,516,264	1,169,637	8,989,806	
	16,931	1,149	18,079	5,303,904	2,516,264	964,807	8,784,975	
	16,931	9,954	6,885	5,303,904	,516,264	1,244,295	9,064,463	
			6,422	5,303,904	2,265,222	922,693	8,491,818	
	6,422	,274	13,696	5,303,904	2,265,222	1,169,637	8,738,763	
	6,422	,149	7,	5,303,904	,265,222	964,807	8,533,933	
	6,422	9,954	16,376	,303,904	2,265,222	1,244,295	8,813,421	
	47,873	0	47,873	5,303,904	2,802,336	922,693	9,028,933	
	47,873	7,274	,148	,303,904	2,802,336	1,169,637	9,275,877	
		,149	4,	5,303,904	2,802,336	964,807	9,071,047	
	47,873	9,954	57,	5,303,904	2,802,336	1,244,295	9,350,535	
	0	0	58,011	7,403,366	,066,723	922,693	10,392,781	
,011		7,	65,	7,403,366	2,066,723	1,169,637	10,639,726	
58,011		1,149	59,160	7,403,	,066,723	964,807	10,434,896	
		9,954	67,	7,403,366	2,066,723	1,244,295	10,714,384	
011	16,931		74,942	7,403,366	2,516,264	922,693	10,842,323	
	16,931	7,274	82,217	7,403,	2,516,264	1,169,637	11,089,268	
58	16,931	1,149	76,091	7,403,366	2,516,264	964,807	10,884,437	
58,011	16,931	9,954	1,897	,403,	2,516,264	1,244,295	11,163,925	
58,011			64,	,403,366	,265,222	922,693	10,591,280	
58,011	6,422	7,274	71,708	7,403,	,265,222	1,169,637	10,838,225	
011	6,422	1,149	582	7,403,366	,265,222	964,807	10,633,	
58	6,422	9,954	74,	,366	2,265,222	1,244,295	10,912,883	
58,011	47,873	0	105,885	7,403,366	,802,336	922,693	11,128,	
,011	47,873	7,274	,159	7,403,366	,802,336	1,169,637	,339	
,011	47,873	1,149	107,	7,403,366	,802,336	964,807	,509	
58,011	47,873	9,954	115,839	7,403,	2,802,336	1,244,295	11,449,	
011		0	58,011	6,685,129	2,066,723	922,693	9,674,544	
,011		7,274	65,286	6,685,129	2,066,723	1,169,637	9,921,489	
,011		1,149	,160	6,685,129	2,066,723	964,807	9,716,	
011		9,954	67,	6,685,129	2,066,723	1,244,295	9,996,147	
,011	16,931		74,942	6,685,129	2,516,264	922,693	10,124,086	
58,011	16,931		82,217	6,685,129	2,516,	1,169,637	10,371,031	
011	16,931	1,149	,091	6,685,129	2,516,264	964,807	10,166,200	
011	16,931	9,954	84,897	6,685,129	2,516,264	1,244,295	10,445,688	
58,011	6,422		64,	6,685,129	2,265,222	922,693	9,873,043	
,011	6,422	7,	71,708	6,685,129	2,265,222	1,169,637	10,119,988	
011		,149	65,582	6,685,129	,265,222	964,807	9,915,158	
58,011	6,422	9,954	74,388	6,685,129	,265,222	1,244,295	10,194,646	
58,011	47,873	0	105,885	6,685,129	,802,336	922,693	10,410,158	
58	47,873	7,274	113,159	6,685,	2,802,336	1,169,637	10,657,102	
58,011	47,873	1,149	107,033	6,685,129	2,802,336	,807	10,452,272	
58,011	47,873	9,954	115,839	6,685,	2,802,336	1,244,	10,731,760	
195	0	0	265,195	9,116,085	2,066,723	922,693	12,105,500	
65,195		7,274	272,470	9,116,085	2,066,723	1,169,637	12,352,445	
65,195		1,149	266,344	9,116,085	2,066,723	964,807	12,147,615	
		9,954	,150	9,116,085	2,	1,244,295	12,427,103	
65,195	16,931		282,126	9,116,085	,516,264	922,693	12,555,	
65,195	16,931	7,274	289,400	9,116,055	,516,264	1,169,637	12,801,987	
65,195	16,931	1,149	283,275	9,116,085	2,516,264	964,807	12,597,156	
195	16,931	9,954	292,080	9,116,085	,516,264	1,244,295	12,876,644	
	6,422		271,617	9,116,	2,265,222	922,693	12,303,999	
		7,274	278,892	9,116,085	2,265,222	1,169,637	12,550,944	
65,195		1,149	272,766	9,116,	2,265,222	964,807	12,346,114	
65,195	6,422	,954	281,572	9,116,085	2,265,222	1,244,295	12,625,602	
65,195	47,873		,068	9,116,085	2,802,336	922,693	12,841,114	
195	47,873	7,274		9,116,	2,802,336	1,169,637	13,088,058	
65,195	47,873	1,149	314,217	9,116,085	2,802,336	964,807	12,883,228	
65	47,873	9,	323,	9,116,085	2,802,336	1,244,295	13,162,	

If these 64 possible combinations are ranked in order of their per unit cost from lowest to highest, plotting cost and output yields for each combination will produce the potential output curve.

The potential output curve for the working circle inventoried (fig. 1) begins with the option of no management. This would ultimately result in about 8.3 million cubic feet from Standard Land and approximately 361,000 cubic feet from Special Lands (appendix table 15). As the most cost-effective options to spend money are substituted into the curve, it is seen that under full management, and at an on-site cost of approximately $323,000, about 13.6 million cubic feet of wood can be produced annually, including the wood available from Special Land at no cost (appendix table 15). However, to increase output from about 12 million to 13.6 million cubic feet would require nearly a threefold increase in spending.

The flattening of the curve reflects smaller gains in output as management dollar investments increase...

That is, the cost per unit of wood produced is getting larger.

By adding management on Special Land, supplies of wood could be increased, but not very efficiently. Such inefficiency is indicated by the flatness of the curve, which reflects the high marginal cost in relation to marginal output. If Marginal Land became available because of improved technology, additional timber output could be generated.

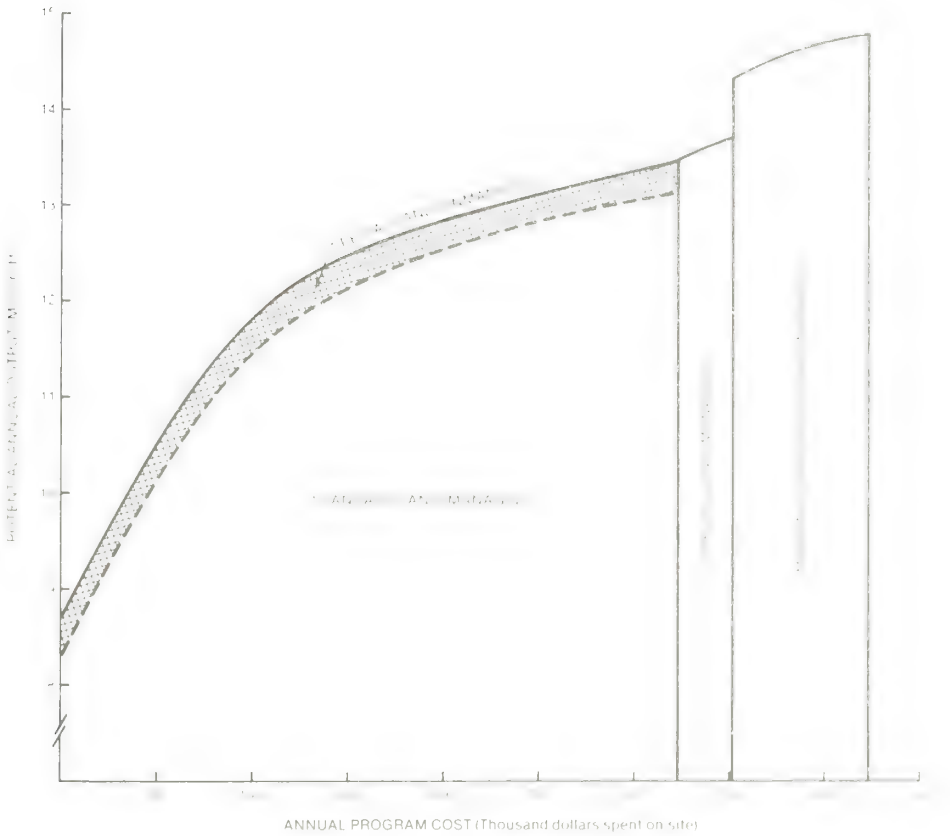


Figure 1.--Potential output curve.

ASSESSING THE PRESENT SITUATION

Monitoring Present Program and Output

The present situation in relation to the potential should be explainable...

■ A COMPARISON. Two kinds of information are generated from basic timber inventory data: (1) an estimate of the sustainable allowable cut (both short and long run), and (2) a plan of management that describes how the short-run allowable cut is to be achieved (usually for a 10-year planning period).

As a beginning point for assessment of the current situation, the available potential output curve has some utility as a monitoring device. If the working circle were in a fully regulated condition, average annual and current annual output and expenditures would be expected to be close to those defined by the curve, given the present harvesting policy of nondeclining even flow.

For a working circle being brought into a regulated condition, average annual or current annual output and expenditures could vary widely from the curve, depending on the nature and character of the existing timber resource and the harvesting schedule in force. For any given year, output or expenditures could be high or low in relation to each other for any of severa reasons.

A high output-low expenditure situation might indicate a harvest fluctuation around some lower average sustained-yield figure that compensates for a lesser harvest in a prior year. A low output-high expenditure situation could represent some "catchup" management effort made possible by increased K-V deposits from a prior year or appropriated P&M money, or both. The point is, however, that by comparing the estimated potential output and associated management costs with the current levels of output and expenditures, the manager has the opportunity to monitor the overall progress of his management program.

but not necessarily judged.

Interpreting Specific Situations

A resource profile can show the manager what he faces.

■ LOOKING AT CLUES. The timber inventory provides data from which a resource profile can be developed. Such information identifies specific management situations or resource conditions that are relatively homogenous in terms of required management input and that must be dealt with in future management to meet timber production goals. In addition, this

information helps [illegible] next planning period and is the basis for estimating the probable output over [illegible] mass of data to some form that makes interpretation of the various resource situations simpler.

LAND-USE [illegible] put is the effectiveness with which available land is used. A look at the stocking situation by land-productivity class provides a starting point for evaluation (table 5).

Effective use of available land is a key factor in achieving output goals.

Sawtimber stands dominate, and the area classified as "nonstocked" does not appear to be excessively large. All nonstocked land is on the poorest sites. These are outwardly good signs; however, a deeper look into the real nature of the stands is required to pass judgment on the effectiveness with which the land is being utilized.

[illegible] : Seedling :

[illegible]	[illegible]	25,875	[illegible]	538,351
[illegible]	[illegible]	1,751	0	71
50+	25,857			
[illegible]	[illegible]	[illegible]	5,549	133,

Nonstocked...

The data for Douglas-fir and ponderosa pine land in table 5 are based on the classification of the sample field plot as to whether or not it is stocked and, if so, the size of trees present. Stand-size classification alone can be misleading because of the way stand sizes are defined. Sawtimber stands need to be only 16.7 percent stocked with growing stock trees and only half the total stocking must be in sawtimber and pole trees. So a stand classified as sawtimber (based on crown occupancy) could have large numbers of smaller diameter trees in it.

understocked...

"misstocked"...

Moreover, even though enough trees may be present to classify the area as stocked with trees, there are the questions of adequacy and desirability of the stocking. The stocking percent at each of the 10 sample points within the field location provides good additional information about the utilization of commercial forest land for timber production (table 6).

or overstocked?

Table 6.--*Commercial forest land by stocking category and productivity class*[1]

Productivity class (ft^3/acre/yr)	Commercial forest land stocked with trees: Live-tree area	Growing-stock area	Cull-tree area	Nonstocked area	Total area[2]
	- - -

Over the entire working circle, 41,[illegible] productivity land are considered [illegible].

The 17,879 acres on ponderosa pine and Douglas-fir land are those without enough trees to be considered stocked and probably are mostly [illegible] reforestation. The 64,[illegible] acres, the remainder [illegible] nonstocked areas and unoccupied space in lightly stocked stands, based on the stocking percent at each of the 10 sample points of the field locations.

There may be no quick remedy apparent for a stocking problem, but

One can argue that it is unreasonable to consider planting all the openings with seedlings and, therefore, pointless to sum up the thousands of openings and classify them as nonstocked.

the situation is exposed for future planning.

Also, adjacent trees may be utilizing some apparently unused open areas. Such an argument misses the significance of such openings in terms of effective use of available land for growing wood.

Effective use of commercial forest land for timber production would seem to indicate reasonably prompt and adequate regeneration and a high proportion of growing-stock trees. From table 6, a Land Effectiveness Index (LEI) can be computed as the proportion of available commercial forest land currently stocked with growing-stock trees.

$$\text{LEI} = \frac{\text{Area occupied by growing-stock trees}}{\text{Total area available}}$$

In this case, only 313,000 acres of the 440,620 available are classed as being occupied with growing-stock trees (LEI 0.71), that is, those trees that would be featured in management. For low-productivity land the LEI is only 0.65 (table 7).

Judgment on the magnitude of the LEI must be tempered by...

Although the Regeneration Index for low-productivity land was 0.81, the LEI for those same acres is only 0.65, an indication that many nongrowing-stock trees occupy the commercial forest land area. Some 55,467 acres (16 percent) of low-site land are occupied by cull trees, which contribute about as much to the timber production as the bare areas they preclude. Again, this does not mean cull stands, but rather nonmerchantable trees (most of which are probably a nonmerchantable species such as juniper) scattered through an otherwise merchantable stand. The area occupied by cull trees and the unused area in lightly stocked stands combine to reduce the effective area contributing to annual output. On the working circle inventoried, data show a total of 127,618 acres are low producers. That area comprises nearly 29 percent of the total commercial forest land and represents a potential production loss of up to 4.3 million cubic feet annually (table 8) on ponderosa pine and Douglas-fir lands.

Table 8.--*Average productivity, stockable area not being used by growing-stock trees, and productivity lost*

Productivity class	Average productivity	Unutilized area	Cumulative total	Production lost	Cumulative total
		Acres			
20-35	33	120,454	120,454	3,974,982	3,974,982
36-50	48	6,055	126,509	290,640	4,265,622
50+	65	1,109	127,618	72,085	4,337,707

consideration of other use goals for the forest area.

Whether any remedy is possible or desirable at present is another question. If the nonstocked area is high-producing livestock range or wildlife habitat that fits into the overall scheme of the management objectives, the situation is not a problem. Rather, it is a measure of the relative values of grazing opportunity, wildlife habitat, and timber.

If on the other hand the timber values outweigh other uses, the situation should be acted upon as existing stands are cut and regenerated in the future. It must be considered now, however, in estimating short-run timber supplies and planning for the future management of the resource.

□ STAND DENSITY AND STRUCTURE. The need or opportunity to improve stand structure to increase output can be assessed by comparing actual average density and tree-size distribution with the density and size distribution represented by a fully regulated forest from which potential yield may be captured.

Stand density and structure of the average stand in a fully regulated forest can serve as a benchmark for determining management needs.

An approximation of average basal area per acre in growing-stock trees by diameter class can be developed for the entire commercial forest land area from total numbers of trees by diameter class and area by productivity class (appendix table 17).

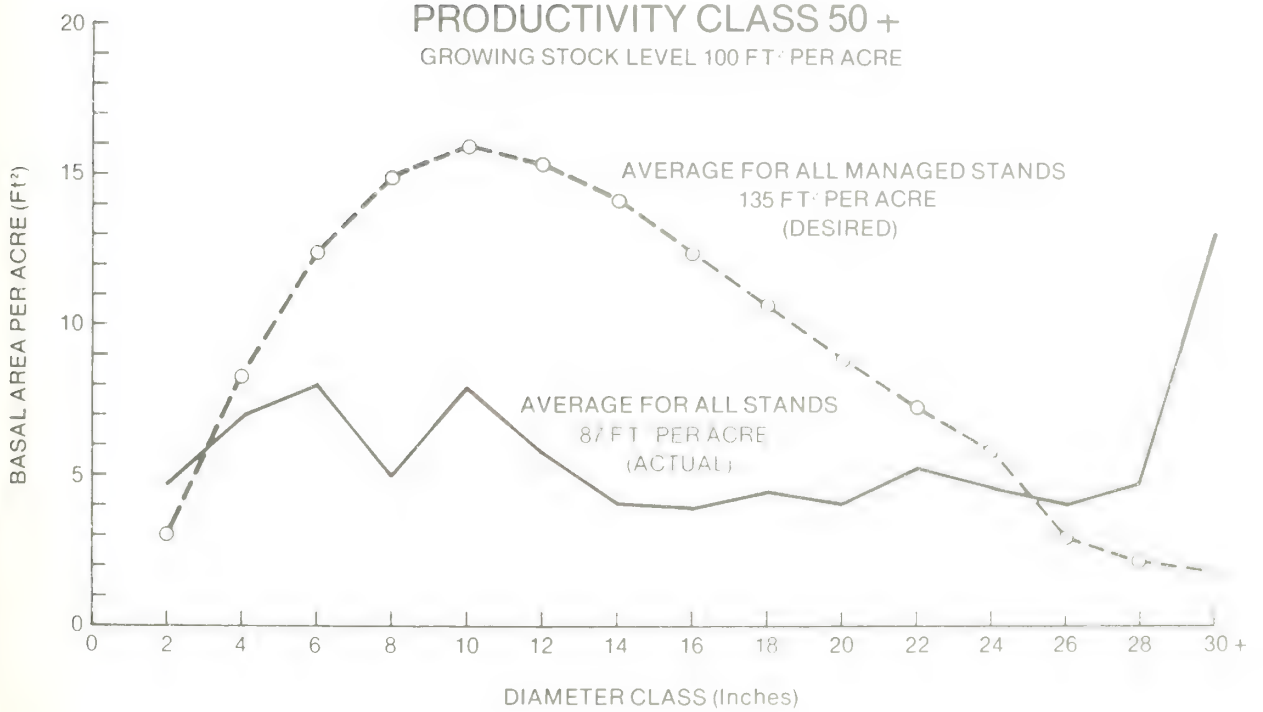
The desired, or target, stand structure can be estimated from known periodic growth rates for a given site quality and the growing-stock level sought for the residual stand after thinning

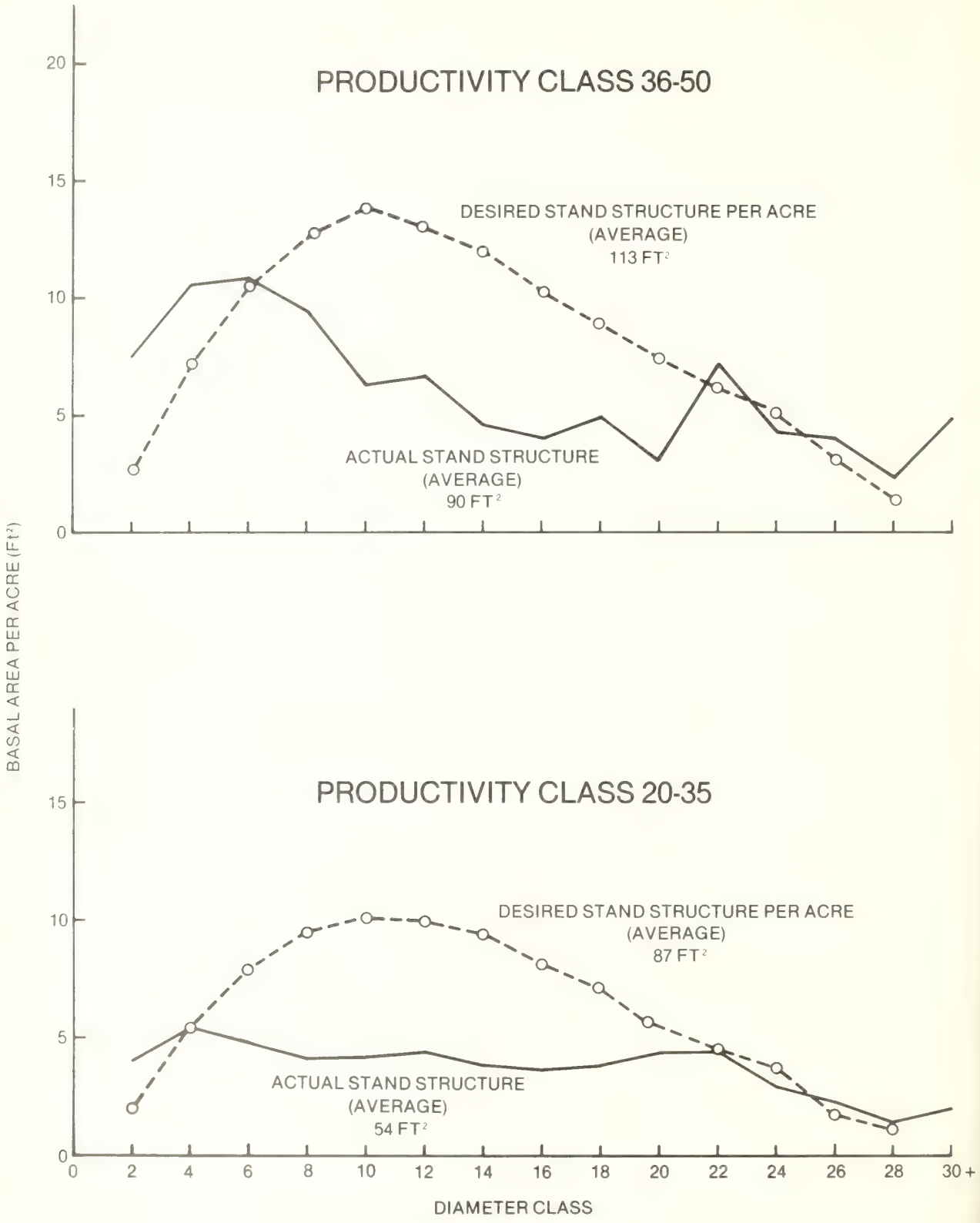
The reason this comparison can be made and has meaning is fairly simple. In dealing with an entire forest or all forest land having a given productivity potential, "average" stocking would approach that of a selection forest. This would be true whether you have even- or uneven-aged management. The cutting cycle, or period, would set the range in actual stocking

and the average [illegible] to represent the problem of the range. [illegible] the trees are growing.

As an example, [illegible] the southwest, ponderosa pine [illegible] 100 on a 20-year cutting cycle [illegible] 0.11 inch per year. The residual 100 square feet of basal area after thinning [illegible] that 20-year period. The average for a collection of these stands whose stage of development would coincide with each year in the cutting cycle would be [illegible] basal area per acre (fig. 2), representing the basal area about 10 years after thinning.

The current actual average for high-site land on the working circle inventoried is only 87 square feet per acre (fig. 2). It is apparent that, in this case, the problem is not one to be solved by an increased thinning effort. While thinning opportunities surely exist in individual stands and could change the diameter distribution to something more closely resembling the desired stand structure (shape of target curve), the problem of stand density will remain. Stocking deficiency can only be solved over a rather long period of time.





diameter class.

An accelerated thinning program could help a stand structure problem but not a stand density problem.

Is this a problem peculiar to [illegible] according to similar data for medium and low sites (fig. 3), even though productivity class 36 to 50 land seems to be in a better position than the lowest site lands. These comparisons support to a great degree some observations made about the adequacy of [illegible] Effective Index.

In figures 2 and 3, the stand structure situation is all but obscured by the low stocking level. [illegible] as indicated by the desired structure of the 135 square feet basal area per acre curve, the basal area in trees less than 10 inches d.b.h. should be about 10 percent of the basal area in trees 10 inches d.b.h. and larger, [illegible] 30 percent of the total basal area. [illegible] growing-stock level maintained. In this case, stands on low- and medium-productivity lands have unduly large proportions of basal area in trees less than 10 inches in diameter (table 9). It appears to be only coincidental that on high-site land basal area is properly distributed between the two size-class groups. The high-basal area in trees 30 inches d.b.h. and larger evidently offsets the low basal area per acre in trees 8 inches in diameter.

Stand structure imbalances also indicate imbalances in age classes that could affect future available output.

In situations like this, the manager must consider some strategies for manipulating the resource to achieve his management goals, or else reduce the target density with the idea of achieving the structure and building up the density during the conversion period. However, [illegible] target density seems to avoid the problem rather than to come to grips with it. A more detailed examination of the resource

Table [illegible]

Productivity class	Basal area per acre			Ratio		Basal area per acre			Ratio	
ft³/acre/yr	d.b.h.<10	d.b.h.≥10	Total	d.b.h.<10 : total	d.b.h.≥10 : total	d.b.h.<10	d.b.h.≥10	Total	d.b.h.<10 : total	d.b.h.≥10 : total
20-35	25.0	61.8	86.8	0.40	0.29	[illegible]	35.3			
36-50	32.8	80.6	113.4	.41	.29	38.0	52.3			.42
50+	1/ 38.5	96.8	135.3	.40	[illegible]	24.9	62.1	87.0	.40	.29

1/ All data in table 9 can be developed from appendix table 17. In figure [illegible] per acre by diameter class are:

d.b.h. 2 inches = 3.0 ft²
d.b.h. 4 inches = 8.2 ft²
d.b.h. 6 inches = 12.3 ft²
d.b.h. 8 inches = 15.0 ft²
Total = 38.5 ft²

to determine the extent of variations in stand densities by productivity class would be useful. It might indicate more clearly the nature and size of the job required to increase, by the end of the conversion period, annual output to a level close to the realistic available potential estimated for the commercial forest land.

A generally understocked forest can have overstocked stands. Tree development reflects the existence of thinning opportunities.

TREE DEVELOPMENT. Actual tree development in relation to potential development under the various stand density and stand structure targets is another indicator of management need in terms of thinning. A Tree Development Index (TDI) compares the actual average tree basal area (BA) and the average tree basal area expected, considering the stand density maintained.

From the inventory data, the diameter of the tree of average basal area can be determined along with stand age. Then, for any given stand age, a diameter can be read. If this is done for each productivity class, a picture of tree development for the existing stand is produced. If diameter growth for specific target stand densities is to be predicted through growth-response studies or calculated from managed-stand volume and yield studies, a Tree Development Index can be calculated.

$$\text{TDI} = \frac{\text{BA of average tree (actual)}}{\text{BA of average tree (expected)}}$$

Gilbert Schubert, principal silviculturist at the Forestry Sciences Laboratory in Flagstaff, Arizona, developed average stand diameters for managed southwest ponderosa pine stands on productivity class 50+ lands and for growing stock levels 30 through 100. Growing-stock level 100 would have an average basal area of 135 square feet on 425 trees:

Growing stock level	Average Stand Basal area ft^2	d.b.h.
50	0.3216	7.7
50	.3154	7.6
60	.3152	7.6
70	.3121	7.6
80	.3114	7.6
100	.3181	7.6
Average	0.3156	7.6

These data represent the average for a fully regulated forest. There are 10,910,000 trees on the 27,263 acres of high-productivity lands, or 400 trees per acre. Actual average basal area per acre is 87 square feet, or 0.2175 square feet per tree. Comparing the expected average diameter of 7.6 (average tree basal area of 0.3181 square feet) with the average

actual tree diameter of 6. [illegible] square feet) yield a Tree Development Index of [illegible]. This indicates some thinning opportunities on high-site lands exist, even though the overall problem of understocking is obvious as indicated in figure 2.

□ [illegible], GROWTH, AND MORTALITY. Volume, [illegible] summaries by land-productivity class (tables 10 and 11) are

Table 10.--[illegible]

Category	PRODUCTIVITY CLASS			
	20-[illegible]	[illegible]-50	50+	
		Ft^3		
Net growing stock volume in:				
[illegible] trees	104,189,671	31,553,321	19,572,047	
Acceptable trees	216,419,870	78,927,300	42,495,384	
Total	[illegible]	110,480,621	62,067,431	193,157,593
Volume in:				
Rough trees	5,495,694	[illegible]	1,055,080	
Rotten trees	[illegible]	157,142	[illegible]	
Total	5,841,531	2,670,955	[illegible]	9,650,502
Total volume	526,451,072	113,151,574	63,205,249	[illegible]
Net growth (per year):				
Softwoods	5,226,255	2,113,557	[illegible]	7,955,452
Hardwoods	-38,376	2,221	107,311	71,159
Total	5,187,879	2,115,778	[illegible]954	8,006,611
Mortality (per year):				
[illegible]	[illegible]1	411,595	547,548	1,821,692
Hardwoods	[illegible]	0	6,015	
Total	1,161,404	411,595	[illegible]1	1,926,558
Gross growth (per year):				
Softwoods	6,292,006	[illegible],525,150	942,988	[illegible]
Hardwoods	57,277	[illegible]	[illegible]	
Total	6,349,283	[illegible],527,571	[illegible]1	[illegible]
Potential growth for softwoods				
[illegible]	[illegible]3	5,132,000	1,772,09[illegible]	[illegible]

Table 11.--*Per acre volume, growth, and mortality for the stocked area and the area stocked with growing-stock trees by land-productivity class*

Category	Land-productivity class			Total
	20-35	36-50	50+	
	STOCKED AREA (ACRES)			
	341,857	71,500	27,263	440,620
	- - - - - - - - - - - - - - - - Ft^3/acre - - - - - - - - - - - - - - - -			
Growing-stock volume	938	1,545	2,277	
Gross growth per year	18.6	35.3	38.7	
Mortality per year	3.4	5.8	13.0	
Net growth per year	15.2	29.6	25.8	
	AREA STOCKED WITH GROWING-STOCK TREES (ACRES)			
	221,403	65,445	26,154	313,002
	- - - - - - - - - - - - - - - - Ft^3/acre - - - - - - - - - - - - - - - -			
Growing-stock volume	1,448	1,688	2,373	
Gross growth per year	28.7	38.6	40.4	
Mortality per year	5.2	6.3	13.5	
Net growth per year	23.4	32.3	26.9	

Past management generated present growth. The effectiveness of such management should be examined.

a major source of insight into the current status and performance of the timber resource. Because recent performance is largely the result of past management, such data provide a base for judging the adequacy of the present timber-growing program as well as some clues for future management direction and emphasis.

Current annual production is actually a measure of periodic annual increment, but production potential is measured as mean annual increment. Obviously, these two measures of growth are not comparable except for fully regulated forest areas. While such comparisons have no validity for judging the performance of an individual stand, they do have meaning for a general overview of a working circle.

Δ MANAGEMENT EFFECTIVENESS. The effect of past management can be partially gaged by a Management Index that compares potential per acre annual growth with recent actual growth (table 7). This index is computed by using net annual growth and potential growth for softwoods from table 10.

Management I =

$$\frac{\text{Net growth per acre}}{\text{Potential growth per acre}}$$

Management I $\frac{7,933,152}{10,185,376}$ = 0.78 for the entire working circle,

with the performance of high-site land even less (0.69).

Mortality I,

Total net annual growth / Total gross annual growth

Mortality is the first factor that comes to mind in the search for explanation. A Mortality Index can be used to help explain the Management Index value.

Mortality does not necessarily deserve all the blame for low net growth rates.

This computes to 0.81 for all commercial forest land on the working circle inventoried (table 7). Note, however, that a much higher Mortality Index is indicated for high-site land. This can be attributed to a wildfire that prior to the inventory, burned over nearly 20,000 acres, mostly better quality land occupied by ponderosa pine. But, does mortality alone account for the difference between potential and actual growth? A clue can be found by another Management Index that relates gross growth to potential.

Management II =

Total gross growth per acre / Total potential growth per acre

This index value for the working circle inventoried averages 0.60 for all commercial forest land (table 7), a figure too low to justify attributing the entire difference between actual and potential growth to mortality that only claimed 19 percent of gross growth. In the previous section, it was noted that only 71 percent of the area available actually was stocked with growing stock. That would account for part of the growth gap. Also, stand density appeared to be significantly deficient on all commercial forest land.

The output possibilities and the present situation can be shown and examined graphically.

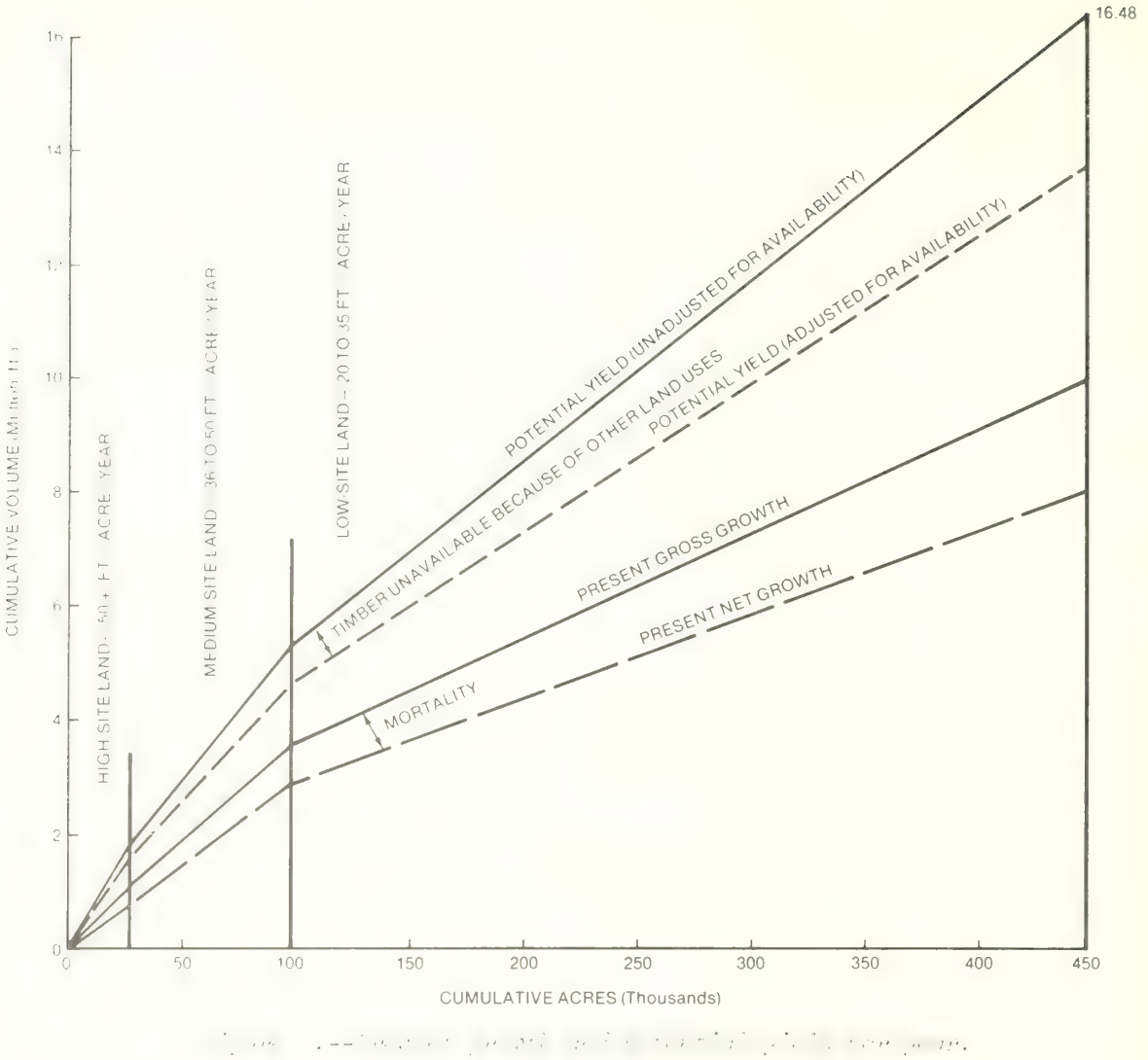
In table 11, volume and growth on the working circle inventoried have been summarized by land-productivity class for the stocked area and for the area stocked with growing-stock trees. Some interesting comparisons can be made between current and potential output.

The relation of current growth to potential yields can also be shown graphically (fig. 4). Beginning with the most productive land, volumes and acres are cumulatively summed, adding in less and less productive land. The volume figures are the per acre values multiplied by the number of acres; the data are from table 11.

The disquieting feature of this comparison is, of course, the big gap between present net growth and the future potential available yield. What are the opportunities for increasing output through more intensive management?

Present output in relation to expectations from increased management activities can be revealing.

In developing the potential output curve, four levels of management with their associated costs and expected output were considered. If the expected annual yields given for the four levels of management are applied to all the area in each productivity class, a graphic display similar to figure 4 can be generated (fig. 5). Again, cumulative totals are used, but only Standard Land has been used to illustrate the method.

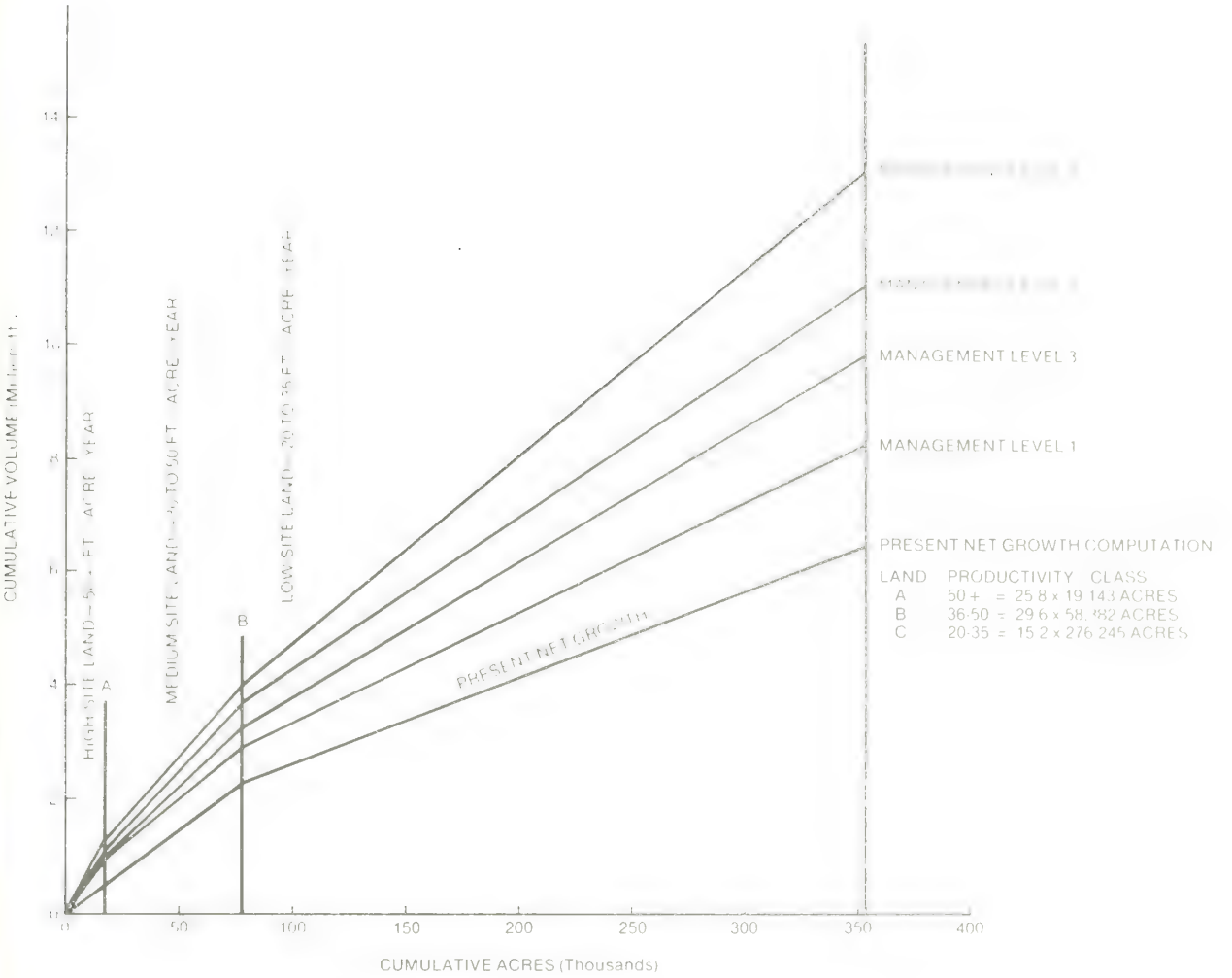


One ridiculous conclusion that might be drawn from the graph is that the annual yield could be increased by nearly 2 million cubic feet merely by stopping all management.

Opportunities for increasing output can be shown from this kind of analysis...

The expected levels of output for each management level are for a fully regulated forest and predicated on the assumption that all the available land would be adequately stocked eventually, even at Level 1 (no management). The important point of figure 4 is the extent of the opportunity to increase timber supplies by increasing net growth using whatever means may be most appropriate. This possibility should come as no surprise considering some of the "clues" developed in previous sections:

1. A sizable area of land is nonstocked, understocked, or occupied by cull trees.
2. Average stand density is considerably less than desired.



but the manager must decide what must be done and consider the costs involved when planning his future approach for accomplishing his goals.

standpoint of timber production.

According to figure 5, given adequate stocking, the present actual net growth on Standard Land could be achieved by intensively managing only [illegible]. However, [illegible] is question of what could be done [illegible] the commercial forest land involved.

Further disaggregation of the commercial forest land into specific situation categories, such as sparse sawtimber stands, [illegible] ated cutover areas, will identify real management opportunities. These opportunities can then be evaluated on the basis of treatment costs and expected responses or value returns to develop rational management strategies that are economically efficient in realizing production goals.

APPENDIX

Table 12

STANDARD LAYO

Avail. class	Land prod. class	Acc.	Mgt. level	Regen. period	Growing period	Rotation	Yield expected: Per acre: total	Yield expected: Per acre: per acre	Management costs/acre: Regen	Management costs/acre: P C thin	Management costs/acre: Other	Management costs/acre: Total	Production costs: Per unit: Yield	Production costs: Annual: per acre
(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
I	20-35	35	1	2	95	120	2,400	20.0	0	0	0	0	0	0
	V[1]		2	25	95	120	5,215	36.8	0	15	10	25	0.008	0.21
	(Acres)		3	5	115	120	2,901	21.2	25	0	0	25	.009	.21
	276,245		4	5	117	120	5,960	55.0	90	15	10	115	.020	.96
	36-50	48	1	15	105	120	4,250	55.1	0	0	0	0	0	0
	B		2	15	105	120	5,169	43.1	0	20	15	35	.007	.29
	(Acres)		3	5	115	120	1,655	38.8	15	0	0	15	.005	.11
	58,582		4	5	117	120	5,760	48.0	65	20	15	98	.017	.82
	50+	65	1	10	110	120	5,790	48.2	0	0	0	0	0	0
	C		2	10	110	120	7,351	61.1	0	25	20	45	.006	.38
	(Acres)		3	5	115	120	6,051	50.4	7	0	0	7	.001	.06
	19,143		4	5	117	120	7,800	65.0	17	25	20	62	.008	.52

Total area (Acres)
555,770

[1] See table 3, footnote 2.

Table 15

SPECIMEN TABLE

Stand class	Land prod. class	Age	Mgt. level	Progm. period	Growing rotations	Yield expected: Per acre total	Per acre per year	Management cost: Per acre per year	Thin	Other	Total	Production costs: Per unit cut	Annual per acre
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	[illegible]	17	1	25	25	1,250	50.0	0	0	0	0	0	0
			2	25	25	1,250	50.0	0	15	10	25	0.005	0.1
	Acres		3	5	115	1,250	21.2	25	0	0	25	.003	.1
	2,085		4	5	117	1,250	55.4	50	15	10	115	.019	.96
	[illegible]	18	1	15	105	1,250	55.4	0	0	0	0	0	0
			2	15	105	1,250	45.1	0	0	15	25	.005	.29
	Acres		3	5	115	1,250	58.8	15	0	0	15	.003	.11
	72		4	5	117	1,250	48.0	65	20	15	85	.017	.82
	[illegible]	65	1	40	110	1,250	48.	0	0	0	0	0	0
			2	40	110	1,250	61.1	0	25	20	45	.008	.37
	Acres		3	5	115	1,250	50.1	5	0	10	5	.001	.06
	14		4	5	11	1,250	65.0	15	25	10	55	.009	.7

Total Acres Acres
1,250

Table 15.--[illegible]

SPECIAL LAND

Avail. class (1)	Land prod. class (2)	Ac.	M.t. level (3)	Regen. period (4)	Growing period (5)	Rotation (6)	Yield expected: Per acre total (7)	Per acre per year (8)	Management costs/acre: Regen. (9)	P.C. thin (10)	Other (11)	Total (12)	Production costs: Per unit yield (13)	Annual per acre (14)
				(Years)			(Cubic feet)		(Dollars)				(Cubic feet)	(Dollars)
II	20-35	35	1	25	95	120	2,160	18.0	0	0	0	0	0	0
			2	25	95	120	2,894	24.1	0	15	15	60	0.021	0.50
	(Acres)		3	5	115	120	2,615	21.8	25	0	0	25	.010	.21
	10,228		4	5	117	120	3,560	29.7	90	15	45	150	.042	1.25
	36-50	48	1	15	105	120	3,825	31.9	0	0	0	0	0	0
			2	15	105	120	4,652	38.8	0	20	50	70	.015	.58
	(Acres)		3	5	115	120	4,189	34.9	15	0	0	15	.003	.11
	2,447		4	5	117	120	5,184	43.2	65	20	50	135	.026	1.11
	50+	65	1	10	110	120	5,211	43.4	0	0	0	0	0	0
			2	10	110	120	6,601	55.0	0	25	55	80	.012	.67
	(Acres)		3	5	115	120	5,449	45.4	7	0	0	7	.001	.06
	459		4	5	117	120	7,020	58.5	17	25	55	97	.014	.81

Total Area (Acres)
13,134

(Con.)

Table 15. [illegible]

[illegible]

Wash. land prod. class (1)	[illegible]	Wet. class (2)	Mat. period (3)	Plant. period (4)	Rotation (5)	Yield expected per acre: total (6)	per year (7)	Management costs per acre: Fert. (8)	P C thin (9)	Other (10)	total (11)	Production costs per unit: yield (12)	Annual per acre (13)
			(yrs)	(yrs)	(yrs)	(MBF)	(MBF)	($)	($)	($)	($)	($)	($)
III	50-37	SS	1	25	95	120	160	2.0	40	0	0	0	40
			2	25	95	120	22	1.7	0	20	20	.20	0.42	0.42
	Acres 81		3	5	115	120	200	2.1	15	0	0	1	.05	.12
	15,362		4	5	117	120	896	5.5	5	20	20	45	.10	.54
	36-30	IS	1	15	105	120	135	1.5	30	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
			2	15	105	120	317	1.5	0	25	25	.01	.110	.59
	Acres		3	5	115	120	166	1.9	10	0	[illegible]	10	.025	.08
	5,095		4	5	117	120	526	1.8	10	25	35	70	.133	.35
	30+	SS	1	10	110	120	370	1.8	0	0	0	0	[illegible]	[illegible]
			2	10	110	120	255	6.1	0	30	40	70	.095	.38
	Acres 4		3	5	115	120	600	5.0	0	0	0	0	.038	.14
	1,095		4	5	117	120	780	6.5	5	30	40	75	.096	.24

Total area: Acres
1,752

Table 15.--[illegible]

SPECIAL LAND

Availability class (1)	Land productivity class (2)	Ave. (3)	Mgt. level (4)	Regen. period (5)	Growing period Rotation (6)	Yield expected: Per acre total (7)	Yield expected: Per acre per year (8)	Management costs/acre: Regen. (9)	Management costs/acre: P.C. thin (10)	Management costs/acre: Other (11)	Management costs/acre: Total (12)	Production costs: Per unit yield (13)	Production costs: Annual per acre (14)
IV	20-35	35	1										
			2										
	(Acres)		3										
	15,732		4										
	36-50	48	1										
			2										
	(Acres)		3										
	2,216		4										
	50+	65	1										
			2										
	(Acres)		3										
	836		4										

ALTEC LANDS UNAVAILABLE UNTIL 1999 (NO YIELD)

Total area (Acres)
16,784
Σ
51,044

Table 11 -

MATERIAL USE

Ward. class (1)	Land prod. class (2)	Acr.	Mgt. level (5)	Regen. period (6)	Growing period (6)	Rotation (6)	Yield expected: Per acre total (7)	Per acre per year (8)	Management costs, acre: Regen. (9)	P.C. (10)	Thin (11)	Other (12)	total (13)	Product unit: Per unit yield (15)	Annual per acre (16)
1	20-35	38	1	55	85	120	1,850	15.6	0	0	0	0	0	0	0
			2	55	85	120	2,877	24.0	0	75	75	150	.052	1.25	
	(Acres)		3	5	115	120	2,350	21.1	80	0	0	80	.032	0.67	
	12,139		4	5	115	120	3,060	30.0	150	75	75	300	.076	2.50	
	36-50	18	1	25	95	120	3,812	31.8	0	0	0	0	0	0	
			2	25	95	120	4,077	34.0	0	80	80	160	.054	1.33	
	(Acres)		3	5	115	120	4,015	38.2	60	30	30	60	.015	.50	
	4,735		4	5	115	120	5,760	48.0	240	80	80	240	.050	2.00	
	50+	43	1	10	110	120	4,750	39.2	0	0	0	0	0	0	
			2	10	110	120	5,565	46.1	0	80	80	170	.025	1.17	
	Acres		3	2	115	120	4,671	38.9	80	0	0	80	.017	.67	
	2,047		4	2	115	120	5,400	45.0	240	80	80	320	.059	2.67	

Total Area Acres
2,773

Table 11.--

MARGINAL LAND

Avail. class (1)	Land prod. class (2)	Ave.	Mgt. level (3)	Regen. period (4)	Growing period (5)	Rotation (6)	Yield expected: Per acre total (7)	Per acre per year (8)	Management costs/acre: Regen. (9)	P.C.thin (10)	Other (11)	total (12)	Production costs: Per unit yield (13)	Annual per acre (14)
V	20-35	55	1	40	80	120	820	6.8	0	0	0	0	0	0
			2	40	80	120	1,353	11.3	0	75	75	150	0.111	1.25
	(Acres)		3	5	115	120	1,179	9.8	80	0	0	80	.068	.67
	2,365		4	3	117	120	1,980	16.5	150	75	75	300	.152	2.50
	36-50	48	1	35	85	120	1,675	14.0	0	0	0	0	0	0
			2	35	85	120	2,092	17.4	0	80	80	160	.076	1.33
	(Acres)		3	5	115	120	2,266	18.9	60	0	0	60	.026	.50
	535		4	3	117	120	2,880	24.0	130	80	80	290	.101	2.42
	50+	65	1	15	105	120	2,800	23.3	0	0	0	0	0	0
			2	15	105	120	3,500	29.2	0	85	85	170	.049	1.42
	(Acres)		3	5	115	120	3,070	25.6	40	0	0	40	.013	.33
	245		4	3	117	120	3,900	32.5	110	85	85	280	.072	2.33

Total Area (Acres)
3,145
28,874

Table 15.--

SPECIAL LAND

Avail. class	Prod. class	Area	Mgt. level	Annual mgt. cost per acre	Annual yield per acre	Management cost per year (3) x (1)	Yield expected per year (4) x (1)	Cost per M cubic feet (5) : (6)	Rank
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
1	20-35	1,088	1	0	20.0	0	21,760	0	1
			2	0.21	26.8	228.48	29,158	7.84	6
	A		3	.21	21.2	228.48	26,530	8.68	8
			4	.96	55.0	1,044.48	55,904	29.09	10
	36-50	272	1	0	55.4	0	9,629	0	1
			2	.29	45.1	78.88	11,725	6.73	5
	B		3	.11	38.8	29.92	10,554	2.85	3
			4	.82	48.0	223.04	13,056	17.08	9
	50+	11	1	0	48.2	0	675	0	1
			2	.58	61.6	7.52	862	8.17	4
	C		3	.06	50.1	0.84	706	1.19	2
			4	.37	65.0	7.28	910	8.00	7
	Total area	1,371							

See table 5, footnote 2.

Table 15. [illegible]

SPECIAL LAND

Writ. class	Prod. class	Area	Mgt. level	Annual mgt. cost per acre	Annual yield per acre	Management cost per year (3) x (1)	Yield expected per year (4) x (1)	Cost per 1 cubic foot (5) ÷ (6)	Rank
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
II	20-35	10,228	1	0	18.0	0	184,104	--	1
			2	0.50	24.1	5,114.00	246,193	20.75	8
	A		3	.21	21.8	2,147.88	222,970	9.63	4
			4	1.25	29.7	12,785.00	305,772	42.09	10
	30-50	2,447	1	0	31.9	0	78,059	--	1
			2	.58	38.8	1,419.26	94,944	14.95	7
	B		3	.11	34.9	269.17	85,400	3.15	3
			4	1.11	43.2	2,716.17	105,710	25.70	9
	50+	459	1	0	43.4	0	19,921	--	1
			2	.67	55.0	307.53	25,245	12.18	5
	C		3	.06	45.4	27.54	20,859	1.32	2
			4	.81	58.5	371.79	26,852	13.85	6
	Total area	13,134							

(con.)

Table 13.—

SPECIAL LAND

Wetland class	Productivity class	Area	Mgt. level	Annual cost per acre	Annual yield per acre	Management cost per year	Yield certified per year	Cost per thousand feet	Rank
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
III	20-35	15,564	1	0	0	0	$1,158	0	4
			2	0.42	1.7	6,537	12,025	155.50	9
			3	.15	2.4	2,027	57,534	54.10	1
			4	.51	3.5	8,105	31,561	165.45	10
	36-50	5,000	1	0	0.5	0	10,532	0	1
			2	.56	1.3	1,518	15,405	116.25	7
			3	.08	2.0	216	12,170	20.50	5
			4	.58	1.8	1,750	31,500	150.55	6
	51+	1,000	1	0	1.85	0	2,220	0	2
			2	.72	2.7	1,944	7,560	90.00	8
			3	.28	3.0	1,008	7,560	90.00	8
			4	.72	3.5	2,592	7,182	0	3
Total or average		20,564							

Table 15.--Cont.

SPECIAL LAND

Avail. class	Prod. class	Area	Mgt. level	Annual mgt. cost per acre	Annual yield per acre	Management cost per year (3) x (1)	Yield expected per year (4) x (1)	Cost per M cubic feet (5) : (6)	Rank
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ft³/ac/yr	Acres		$	Ft³	$	m³	$	
IV	20-35	13,732	1						
			2						
	A		3						
			4						
	36-50	2,216	1						
			2						
	B		3						
			4						
	50+	836	1						
			2						
	C		3						
			4						
	Total area	16,784							
		Σ							
		51,044							

AZTEC LANDS (NO YIELDS AVAILABLE)

Table No. [illegible]

MARGINAL LAND

Marl. class	Prod. class	Area	Mgt. level	Annual mgt. cost per acre	Annual yield per acre	Management cost per year (5) x (11)	Yield expected per year (11) x (11)	Cost per M cubic feet (13) : (16)	Rank
		(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
I	20-35	19,129	1	0	15.6	0	298,412	0	1
			2	1.25	24.0	23,911	459,096	52.08	9
	V		3	.67	21.1	12,816	405,622	31.72	3
			4	2.50	33.0	47,822	631,257	75.76	10
(Inoperable)	36-50	1,735	1	0	51.5	0	111,785	0	1
			2	1.33	80.0	6,905	177,567	34.10	6
	E		3	.50	66.1	2,576	175,290	12.38	5
			4	.12	45.0	11,018	218,511	50.42	8
	51+	2,017	1	0	15.	0	25,662		
			2	1.17	61.1	2,360	175,377	13.21	4
	C		3	.83	24.1	1,660	145,169	11.43	2
			4	.33	65.0	1,775	175,955	10.09	7

[illegible]

[illegible]

Table 16.-- [illegible]

MARGINAL LAND

Avail. class	Prod. class	Area	Mgt. level	Annual mgt. cost per acre	Annual yield per acre	Management cost per year (3) x (1)	Yield expected per year (4) x (1)	Cost per M cubic feet (5) : (6)	Rank
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	[illegible]	[illegible]		$	[illegible]	$	[illegible]	$	
V	20-35	2,565	1	0	6.8	0	16,082	0	1
			2	1.25	11.3	2,956	26,724	110.61	9
	A		3	.67	9.8	1,585	23,177	68.39	5
			4	2.50	16.5	5,912	39,022	151.50	10
(Steep slope)	36-50	535	1	0	11.0	0	7,490	0	1
			2	1.33	17.4	712	9,309	76.49	7
	B		3	.50	18.9	268	10,112	26.50	3
			4	2.42	21.0	1,295	12,840	100.86	8
	50+	245	1	0	23.3	0	5,708	0	1
			2	1.42	29.2	348	7,151	48.64	4
	C		3	.33	25.6	81	6,272	12.91	2
			4	2.33	32.5	571	7,962	71.72	6
	Total area	3,145							
		Σ							
		28,874							

Table 17.--*[illegible]*

Diameter class	Existing stands: Productivity class			Average natural stand: Productivity class		
	20-35	36-50	50+	20-35	36-50	50+
2	3.9	7.5	4.9	2.0	2.6	3.0
4	5.4	10.5	7.0	5.5	7.1	8.2
6	4.8	10.7	7.9	8.0	10.3	[illegible]
8	4.2	9.3	5.1	9.5	12.6	[illegible]
10	4.2	6.1	8.0	10.2	13.7	15.9
12	4.4	6.6	5.8	9.8	13.2	15.3
14	3.8	4.5	5.9	9.3	12.0	[illegible]
16	3.7	3.9	5.6	8.3	10.3	[illegible]
18	3.6	4.9	4.5	7.1	8.6	[illegible]
20	3.8	3.0	4.0	5.7	7.4	8.9
22	3.9	7.4	5.8	4.7	6.2	7.2
24	2.8	4.4	4.6	3.7	5.0	5.8
26	2.2	4.1	4.1	1.8	2.9	2.7
28	1.2	2.4	4.7	1.2	1.3	[illegible]
30+	1.7	5.0	13.1	0	0	1.7
Total	55.6	90.3	87.0	86.8	113.4	[illegible]

[illegible] U.S. GOVERNMENT PRINTING OFFICE [illegible]

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AMERICAN REVOLUTION BICENTENNIAL
1776-1976

GROWING
FROM
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CENTENNIAL

VEGETAL DEVELOPMENT ON THE SLEEPING CHILD BURN IN WESTERN MONTANA, 1961 to 1973

L. Jack Lyon

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L. JACK LYON, Wildlife Research Biologist, has been leader since 1962 of the research work unit devoted to ecology and management of wildlife habitat. This unit is headquartered at the Forestry Sciences Laboratory on the campus of the University of Montana. His studies in postfire forest succession are widely recognized as a unique and continuing contribution to the understanding of seral vegetation dynamics. Dr. Lyon holds both a B.S. and an M.S. degree in Wildlife Management from Colorado State University, as well as his Ph.D. degree in the same field from the University of Michigan. He has authored over 30 technical publications and articles. He is a life member of the Wildlife Society and a member of the American Institute of Biological Sciences, Society for Range Management, and Ecological Society of America.

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ABSTRACT

In the year following the 1961 Sleeping Child forest fire on the Bitterroot National Forest, Montana, 11 permanent transects were established within the burn. Vegetation development was recorded through 1973, but only four transects were considered indicative of seral forest succession independent of superimposed management activities including salvage logging, cattle grazing, and chemical thinning of tree seedlings.

Tree-seedling attrition amounted to 48 percent of established plants in 11 years and shrub-crown volumes exceeded 2,000 ft^3/ acre, while cover at ground level reached nearly 60 percent. Vegetal cover by introduced grasses was an important component of these plant communities for 6 to 8 years.

Major modifications in plant community structure resulted from management activities, but none of the existing communities are considered completely atypical.

INTRODUCTION

During the period August 4 through 9, 1961, more than 28,000 acres of high-altitude forest on the Bitterroot National Forest burned in a high-intensity, lightning-caused wildfire. With the exception of some small islands of unburned forest, the general visual impression was that all vegetation had been reduced to blackened stems and ashes (fig. 1). At the time, the Sleeping Child fire was the single largest forest fire in the Northern Rockies in more than 20 years. Thus, it presented a unique opportunity to record postfire vegetal recovery and development in the upper montane and subalpine forest zones of Montana.

Figure 1.--Transect 5001, August 16[illegible].

During the summer of 1962, 12 permanent transects were established near the center of the burn in the area around the Sleeping Child, Rye Creek, and Martin Creek Divides. One transect was located on a patented mining claim, and at the request of the operator it was removed. The remaining 11 transects represented all aspects, except due east, at altitudes between 6,400 and 7,200 feet. At these elevations on the Bitterroot National Forest, lodgepole pine is the dominant tree species, but forest communities are mostly classified as *Abies lasiocarpa/Xerophyllum tenax* habitat type.[1] Transects above 7,000 feet appear to be *Vaccinium scoparium* phase while those at lower elevations are *Vaccinium globulare* phase.

The initial objectives of this study specified annual sampling for a period of 10 to 15 years to document early postfire vegetal development in a predominantly lodgepole pine forest. However, and unfortunately for the initial study objectives, the Sleeping Child burn also created a series of unusual land management problems. Postfire rehabilitation of the high-altitude watershed was considered a management necessity. Immediate salvage logging was required to prevent the loss of a substantial volume of timber. The growth of grasses and forbs provided an opportunity to relieve grazing pressure on cattle allotments elsewhere on the Bitterroot National Forest, and the obvious overstocking of lodgepole pine seedlings led to intensive efforts to reduce tree densities throughout the burn. Management personnel did attempt to mark and protect the research transects, but changes in staffing and the pressures of project planning have resulted in a continuous attrition of undisturbed sample areas. At the completion of the 1973 field season, there were only two transects remaining which had not been compromised in one or more ways.

Although the collected information does not represent undisturbed postfire forest succession, the study still has considerable value. Each of the transects provides a case study of forest vegetation development, and comparison of disturbed and undisturbed transects provides both an evaluation of treatment effects and a demonstration of stability and assimilative capacity in these high-altitude forest communities. Finally, and despite some fairly substantial short-term modifications, there is an overall consistency of pattern which suggests that some facets of early seral succession can still be predicted from the available data.

[1]Pfister, Robert D., Bernard L. Kovalchik, Stephen F. Arno, and Richard C. Presby. 1974. Forest habitat types of Montana. Intermountain Forest and Range Experiment Station and Northern Region, USDA Forest Service, Missoula, Montana. 167 p. (mimeo).

METHODS

Transects were located to provide a range of slopes, aspects, and altitudes present in the burn (table 1). Insofar as possible, the sampling areas were confined to uniform topography. Each transect consisted of 10 circular plots, 23.55 feet in radius (0.04 acre), with a paired 2- by 2-foot plot inside. Large plot centers were spaced at 50-foot intervals and permanently marked with 3/8-inch steel pins. Secondary steel pins, located 10 feet uphill from the large plot centers, provided permanent location points for the small plots.

Vegetation sampling in the large plots consisted of a total count, by species, of all trees and shrubs more than 6 inches tall. In addition, 5 to 10 random shrubs of each species in each plot were measured on two dimensions of the plant crown (a, b) and height (h) to the nearest inch. These data were converted to crown volume ($V = \pi abh/4$) and the averages for measured plants were applied to the count data to obtain crown-volume estimates for the transect. Data recorded in the 2- by 2-foot plots included tree seedling density, vegetal cover to the nearest quarter-plot, and frequency of occurrence for all species under 18 inches tall.

Transects were established during the first postfire growing season (1962) and sampled annually through 1967 and semiannually thereafter through 1973. Six of the transects were also sampled in 1970 in an attempt to assess herbicide effects.

All data in this paper are presented in English units. Conversion to metric units requires the following constants:

Inches × 2.540	= centimeters
feet × 0.305	= meters
f^3 × 0.028	= m^3
f^3/acre × 0.070	= m^3/hectare
acres × 0.405	= hectares
density/acre × 2.471	= density/hectare

Table 1.--*Physical descriptions of transects, Sleeping Child burn*

	Transect										
	01	02	04	05	06	07	08	09	10	11	12
Aspect (azimuth)	10	205	355	335	315	5	200	125	205	50	285
Altitude (100 ft)	72	72	66	64	65	67	68	71	68	70	64
Slope (percent)	40	35	35	30	20	25	20	15	40	47	30

MANAGEMENT ACTIVITIES AND TREATMENTS

The Darby and Sula Ranger Districts have had active watershed rehabilitation, timber salvage, timber stand improvement, deadwood sales, and grazing programs on the Sleeping Child burn. In addition, the burn has been an important source of firewood, corral poles, and fenceposts for Ravalli County residents. Insofar as records are available, these activities are summarized by year in table 2.

Table 2.--*Summary of management actions and other activities on the Sleeping Child burn, 1962 to 1973*[1]

Activity	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Aerial seeding[2]	A											
Tree planting, acres	500				30							
Road construction, miles	200	A										
Terracing, acres	1,280	A			30	A						
Check dams	1,400											
Stream clearance, miles	22											
Timber salvage, MMBF	76	10	4	3								
Poles and firewood		A	A	A	A	A	A	A	A	A	A	A
Deadwood sales, MMBF						A	A	A	A	A	[4]105	10-15
Christmas trees, bales								100	100	100	100	100
Mechanical thinning[3]				A								
Chemical thinning, acres					126	175	851	1,738				
Mistletoe control, acres						3,132						
Cattle, 3 to 4 months			430	356	408	525	913	787	848	705	610	563

[1] "A" where an activity occurred but no total was recorded.

[2] 180 tons of smooth brome, orchardgrass, hard fescue, annual rye, timothy and Dutch white clover applied by helicopter to the total burned area. These species were recorded on all transects.

[3] Contract defaulted.

[4] Total deadwood sales through 1972.

With few exceptions, it is not possible to describe the specific level of treatment that influenced vegetation development on transects. Salvage logging, and pole and firewood cutting were usually obvious, but cattle use was only recorded when extremely heavy. Herbicide projects, in particular, presented many situations in which chemical sprays[2] were applied by helicopter within one-half mile or less. Two transects were inside the boundaries of spray projects, herbicide-drift effects were either recorded or indicated by curled, brown leaves on vegetation of seven transects, and eight transects were close enough to have received chemical drift even though no effects were seen. Known or suspected treatments for each transect are summarized in table 3.

Table 3.--[illegible]

	Transect										
	01	02	04	05	06	07	08	09	10	11	12
Aerial seeding[1]	1962	1962	1962	1962	1962	1962	1967	1962	1962	1962	1962
Posts or firewood			1967			1967					1966
Pole sale				1965	1967	1969 1970					
Road construction					1967	1967 1970					
Chemical project[3]					1969					1967	
Recorded drift effect			1968	1966	1966	1967	1967 1968			1968	1969
Potential drift			1969	'1967(6) 1968	1967(3)	1966 1967 1969	1966 1967(3)	1968 1969	1969		1966 1967(3
Heavy cattle use[5]					1967	1964 to 1973	1967 1969 1973	1965			

[1] If the distribution of seed was uniform, about 14 lb per acre.

[2] Post or firewood cutting was a relatively minor disturbance as contrasted to a pole sale which usually involved a bulldozer or some other major equipment.

[3] Treatments have been separated to indicate whether the transect was inside a spray area boundary, adjacent to a spray project, or simply within one-half mile of a project.

[4] Number in parentheses indicates the number of times the transect was within one-half mile of a spray project.

[5] Cattle use recorded only where trampling and grazing effects were obvious.

[2]Exploratory applications in 1966 and 1967 involved seven chemicals and 35 formulations. Project applications in 1968 and 1969 used 2,4-D ester and Dacamine 4-D.

TREATMENT EFFECTS

Of the 11 transects that constitute the sample for this study, all were affected by the aerial seeding for watershed protection and only two remained otherwise undisturbed during the 12 years of postfire recovery. Two additional transects were compromised in relatively minor ways, but seven transects received a variety of unplanned treatments, including disturbance by pole sales, cattle grazing, and herbicide applications intended to reduce lodgepole pine densities.

Examination of vegetal development on individual transects reveals several very substantial modifications following these disturbances. On some transects, in a single year, and as an apparent direct result of disturbance, tree densities declined by as much as 60,000 per acre (table 4), shrub-crown volumes were reduced by more than 50 percent (fig. 2), and one-third of the ground-level vegetal cover was removed (fig. 3).

Table 4.--*Tree densities on Sleeping Child transects 1962 to 1973*

Transect	1962	1963	1964	1965	1966	1967	1969	1971	1973
					THOUSANDS OF TREES PER ACRE[1]				
*SC01	T[2]	T	T	T	T	T	T	0.1	0.1
*SC02	4.4	4.4	3.3	4.4	4.4	4.5	2.2	3.8	3.9
SC04	44.6	46.8	43.6	45.7	45.7	38.1	39.0	39.1	39.6
SC05	8.7	17.4	17.4	14.2	10.9	8.7	9.4	11.1	14.9
SC06	75.1	78.4	69.7	64.3	58.8	51.2	52.0	34.4	35.6
SC07	148.1	159.0	151.4	148.1	145.9	129.7	119.8	58.3	69.7
SC08	6.5	7.6	7.6	7.6	7.6	4.7	4.2	1.6	1.7
*SC09	2.2	2.2	2.2	2.2	1.1	1.2	1.3	0.3	0.4
*SC10	29.4	26.1	26.1	27.2	19.6	12.6	15.1	16.5	15.4
SC11	19.6	19.6	16.3	16.3	14.2	9.0	1.4	1.8	3.3
SC12	9.8	8.7	7.6	9.8	9.8	10.0	9.9	9.7	10.2
Average	31.7	33.0	31.4	30.9	28.9	24.5	23.1	16.1	17.7
					THOUSANDS PER ACRE OVER 18 INCHES TALL				
*SC01								0.1	0.1
*SC02						0.1	1.2	2.7	3.9
SC04							0.9	4.2	8.0
SC05							0.7	3.5	6.2
SC06						0.1	1.9	2.8	5.2
SC07						0.1	2.2	10.4	15.2
SC08						0.3	0.9	1.6	1.7
*SC09						0.1	0.2	0.3	0.4
*SC10						0.6	4.2	7.8	11.1
SC11						0.3	0.3	0.7	1.1
SC12						0.2	1.1	4.2	5.9

[1] Estimates prior to 1967 based on projections from 10 small plots (4 ft^2). Variance in these data is extremely high because a single seedling in these plots projects to 1,089 per acre. After 1967, the data include trees over 18 inches tall from the 0.04-acre plots as listed separately in the lower half of the table.

[2] "T" = less than 50 trees per acre.

* Transects considered to be undisturbed.

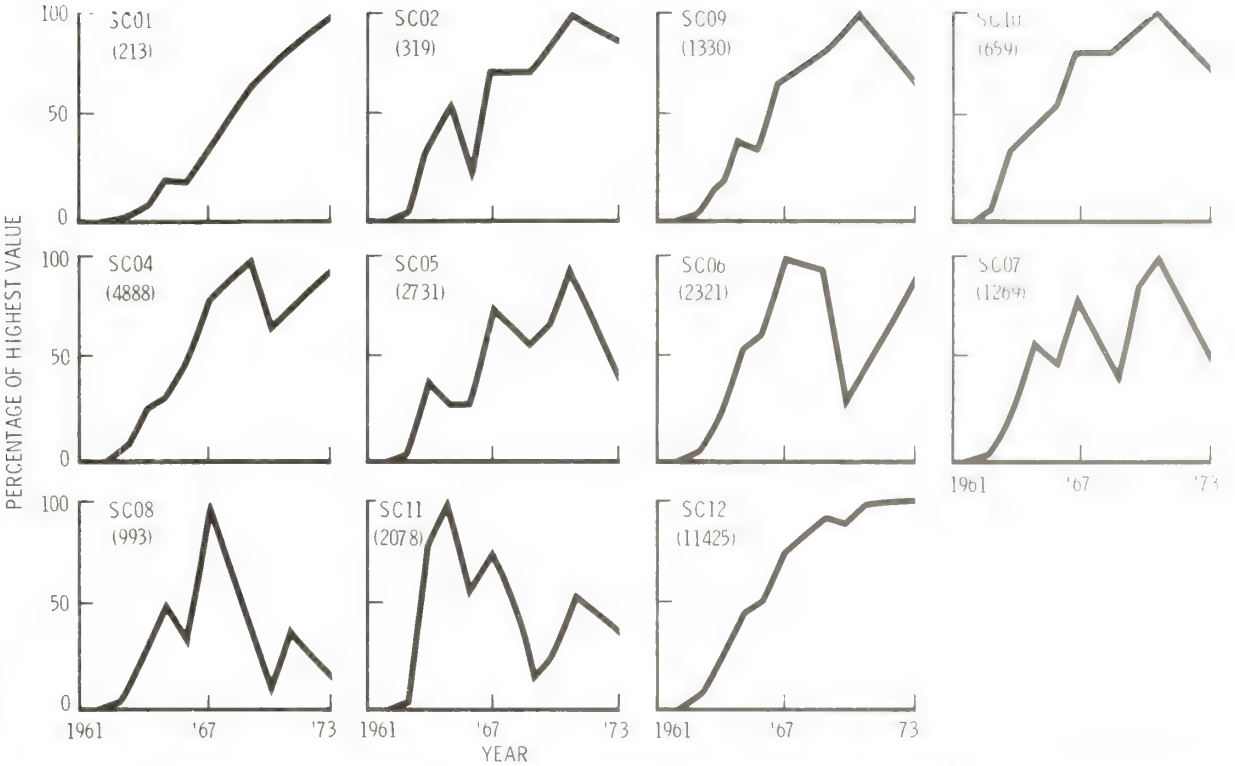


Figure 2.--Shrub-crown volume, Sleeping Child transects, 1961-1973, [illegible] of highest value recorded. Scale peak, ft^3/acre, is indicated in parentheses.

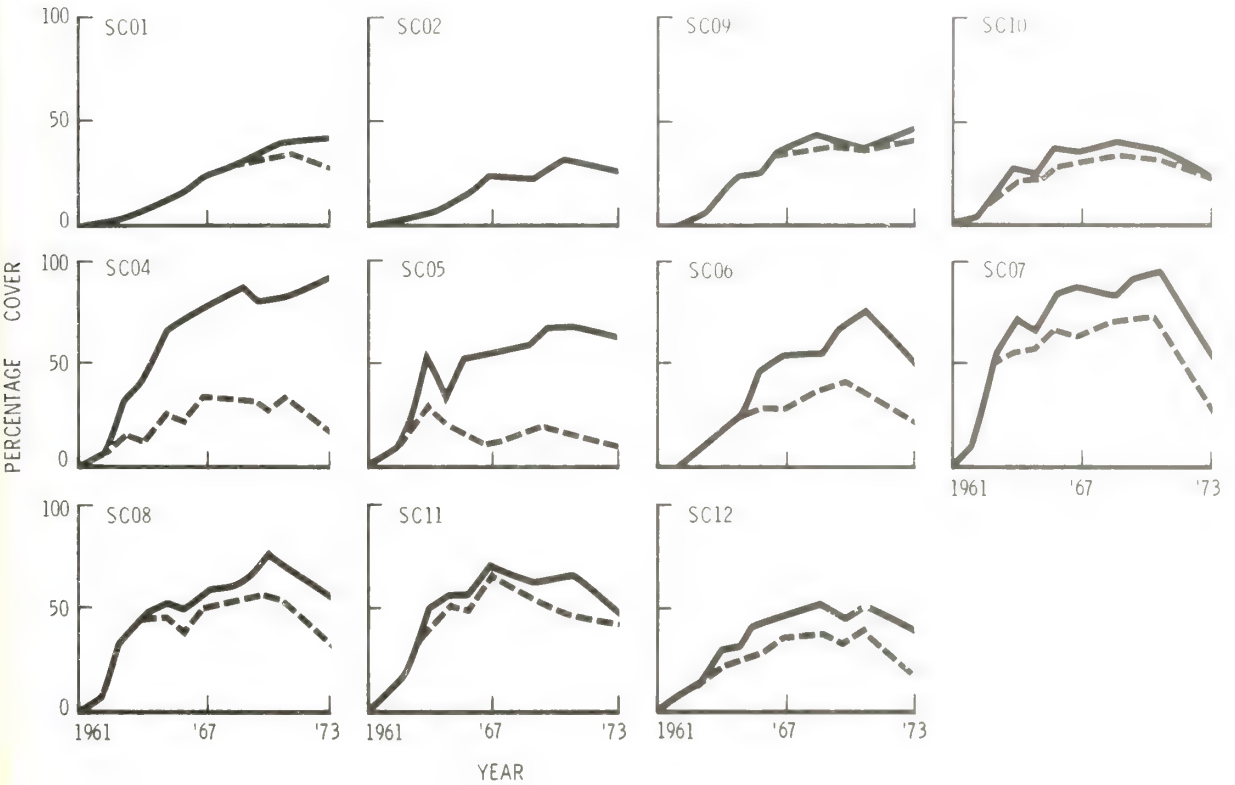


Figure 3.--Percentage vegetal cover (solid line) and vascular cover only (dashed line), Sleeping Child transects, 1961-1973.

Vegetation losses of this magnitude might appear to be disastrous, but long-term evaluation provides a somewhat less conclusive assessment. Attrition of lodgepole pine seedlings would probably have occurred without treatment, and, in no case did a treatment reduce tree densities to the levels expected at forest maturity; many of the shrub-crown declines had been recovered; and vegetal cover on all transects had apparently stabilized by 1970, although community structure was very much modified. Moreover, despite very substantial fluctuations, vegetation development trends for the whole burn appear to be relatively consistent. Thus, in the following discussion I will attempt to evaluate treatment effects by estimating the amount of vegetation which would have been present in the absence of treatments and by comparing trends on the seven disturbed transects with the four transects which received little or no treatment.

To the degree possible, table 5 summarizes the composition, density, and volume changes of vegetation on each transect following recorded treatments, and figures 4 and 5 provide representative examples of vegetal development over the 12 growing seasons of investigation. In each case, any losses in vegetation during the year of treatment or the first year following treatment were assumed to be treatment caused. Because there were no disturbances other than cattle grazing on any transect after 1969, I have assumed that the failure of a species to regain a pretreatment level reached prior to 1970 represents the minimum deficit due to treatments. Ground-level cover deficits will be shown to have occurred at the species level, but none are listed in table 5 because total cover was not significantly reduced.

Tree Densities

The majority of tree seedlings recorded on the Sleeping Child burn were lodgepole pine established in the first growing season. However, some germination took place after the plots were sampled in 1962, and the best estimate of the number of seedling trees established has been taken as the greatest number recorded in either of the first 2 years (table 4). Seedling densities on individual transects ranged from about 100 to nearly 160,000 per acre, with the average for all transects in excess of 34,000. Recorded losses were low for a few years, increased substantially after 1966, and were as high as 80 percent on a few transects. The average annual attrition rate for 11 years was 5.77 percent but there were still 17,700 trees per acre alive in 1973 (fig. 6).

In view of the number of tree seedlings established, an overall loss of 48 percent in the decade can certainly be considered normal. Continuation of the current attrition rate will reduce average tree density to about 1,000 to 1,500 per acre between 50 and 60 years, and even the most conservative estimates of future development would suggest losses of this magnitude can be expected. In consideration of the large die-off already recorded, any conjecture about the course of tree development in the absence of pole sales and chemical thinning must be highly speculative. However, comparison of survival and attrition on the seven disturbed transects with the four undisturbed transects does lead to some surprising conclusions.

For all trees on the four undisturbed transects, annual attrition was 5.26 percent and survival to 1973 was 55 percent. This is not significantly different than the 5.83 percent attrition and 52 percent survival on the seven transects that were eventually disturbed. However, the level of survival on disturbed transects was certainly unexpected considering that at least eight different reductions in seedling density ranging as high as 80 percent were recorded following pole sales or herbicide applications. It is even more surprising when the vegetal composition of the two groups of transects is considered. In the year before management activities were initiated (1965), those transects eventually disturbed averaged five times as many tree seedlings, seven times as much shrub crown, and nearly three times as much vegetal cover as the undisturbed transects. This amount of competing vegetation should have caused tree seedling attrition independent of management activity, and it seems logical to ask whether such competition was, in fact, significant.

Table 5.--[illegible] 1973[1]

Transect	Treatment and single-year decline per acre	Estimated minimum deficit in 1973
C01	No treatments recorded	
C02	No treatments recorded	
C04	1968-69 herbicide: 2,209 ft^3 alder, menziesia, and vaccinium, 6 percent cover of *Vaccinium scoparium*	829 ft^3 alder [illegible] ft menziesia
C05	1965 pole sale and 1966 herbicide: 6,500 lodgepole, 415 ft^3 spiraea, 18 percent cover 1967 herbicide: 390 ft^3 spiraea, vaccinium 1969 herbicide: 353 ft^3 vaccinium	6,500 lodgepole
C06	1965 cattle and 1966 herbicide: 130 ft^3 willow, spiraea 1967 pole sale and herbicide: 7,700 lodgepole, 271 ft^3 rose, vaccinium 1969 herbicide: 17,600 lodgepole, 1,434 ft^3 spiraea, vaccinium, shepherdia, willow, 3 other species	25,300 lodgepole 504 ft shepherdia 280 ft^3 vaccinium 168 ft^3 willow 33 ft^3 3 other species
C07	1964-1966 cattle and herbicide: 198 ft^3 spiraea, vaccinium 1967 herbicide and cattle: 16,200 lodgepole, 345 ft vaccinium 1969-70 herbicide, pole sale, and cattle: 71,400 lodgepole, 118 ft^3 spiraea	87,600 lodgepole 157 ft^3 spiraea
C08	1965 cattle: 182 ft^3 spiraea, vaccinium 1967 herbicide: 3,400 lodgepole, 625 ft^3 spiraea, vaccinium, 3 other species 1969 herbicide and cattle: 2,600 lodgepole, 287 ft^3 vaccinium, spiraea, 3 other species; 8 percent cover of lupine	6,000 lodgepole 434 ft^3 spiraea 119 ft^3 vaccinium 82 ft^3 other species
C09	1965 cattle: 48 ft^3 spiraea, vaccinium 1967 herbicide: 9 ft^3 vaccinium	None
C10	1969 herbicide: 27 ft^3 spiraea	27 ft^3 spiraea
C11	1967-68 herbicide: 12,800 lodgepole, 1,291 ft^3 spiraea, vaccinium, serviceberry, 2 other species, 8 percent cover of lupine	12,800 lodgepole 354 ft^3 vaccinium 40 ft^3 spiraea 40 ft^3 serviceberry 6 ft^3 willow
C12	1966 herbicide: 242 ft^3 spiraea, vaccinium 1967-1969 herbicide: 2,367 ft^3 alder, spiraea, vaccinium, rose	343 ft^3 alder 181 ft^3 spiraea

[1] Scientific names follow Hitchcock, C. Leo, and Arthur Cronquist. 1973. Flora of the Pacific Northwest. Univ. Wash. Press, Seattle, 730 p.

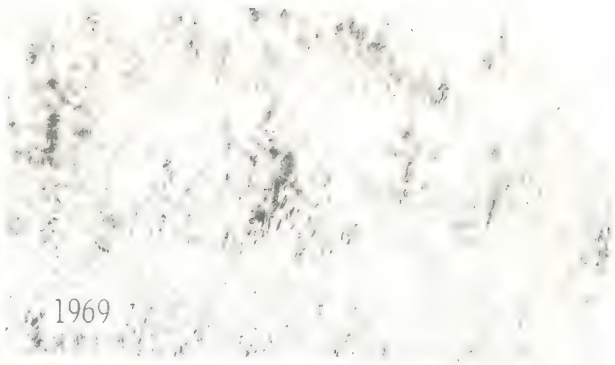
lodgepole - *Pinus contorta*
alder - *Alnus sinuata*
menziesia - *Menziesia ferruginea*
rose - *Rosa gymnocarpa*
serviceberry - *Amelanchier alnifolia*
shepherdia - *Shepherdia canadensis*
spiraea - *Spiraea betulifolia*
vaccinium - *Vaccinium globulare*
willow - *Salix scouleriana*
lupine - *Lupinus sulphureus*

[2] Based on the assumption that an immediate decline or a decline within 1 year following treatment was treatment caused.

[3] Based on the failure of a species to at least recover the pretreatment level. Tree losses are also indicated even though natural attrition also occurred and no recovery was expected. Herbaceous cover deficits appear to have been recovered by species replacement and are not listed here.

Figure 4.--Transect SC02, Sleeping Child burn, 1962 through 1973. Representative vegetal development on a transect with little herbaceous cover.

1962


1969

1963

1971

1965

1973

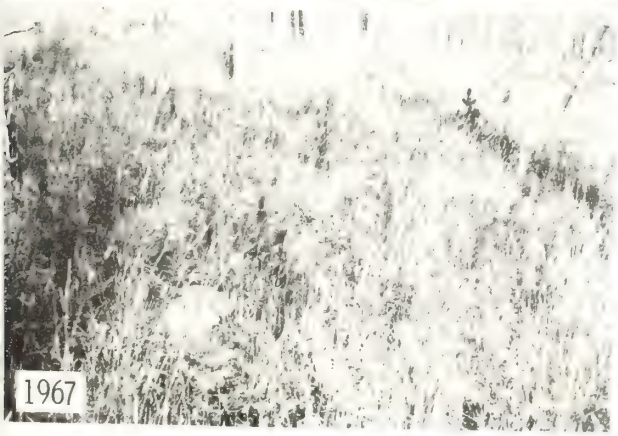

1967

Figure 6.--Transect SC10, Sleeping Child burn, August 1973. Over 15,000 lodgepole pine trees per acre was average for the burned area.

Unfortunately, these data do not suggest a method for delineating the causes of seedling attrition and, in fact, provide very little evidence that recorded disturbances even occurred. The Spearman rank order correlation between seedling density and surviving tree density is $r_s = 0.918$. Moreover, the correlation between seedling density and tree dominance expressed as the percentage of trees over 18 inches tall was $r_s = -0.895$. Thus, trees apparently survived in proportion to postfire seedling densities and, more important, achieved dominance in inverse proportion to seedling densities.

Shrubs and herbaceous cover may also have contributed to these relationships, but the correlations between these variables and tree densities were not significant; and I am unwilling to assign much importance to the relationships with dominance. Tree dominance in 1973 was negatively correlated with both shrub and herbaceous cover as recorded in 1965; but there were enough reductions in shrub and herbaceous cover during the study to suggest that survival of nondominant seedlings may have been enhanced by the removal of competition.

Shrub-Crown Volumes

The average shrub-crown volume for 11 transects in 1973 was 2,076 ft^3/acre, but the seven transects on which disturbance effects were recorded averaged nearly 623 ft^3/acre less shrub crown than minimum predictions of undisturbed development (table 5). It is estimated that shrub-crown volumes would have reached at least 2,700 ft^3/acre by 1973 on the average Sleeping Child transect in the absence of disturbance.

It is not really possible to determine whether this apparent loss of at least one-fourth of shrub-crown volume will be important in the long term. Forty percent of the estimated deficit is the result of alder dieback on two transects. In both cases, the

alder was reduced but not removed from the shrub community. Another third of the deficit is about equally divided between [illegible] and [illegible]. In general, herbicides appeared to have a greater influence in reducing vaccinium, while cattle grazing had a greater influence in depressing spiraea. However, on no transect was either species permanently removed. Reactions of other shrub species were too variable to indicate relative susceptibility to herbicides, but the data generally provided no evidence that dominant species were permanently removed.

Recovery of the deficit shrub crown, on the other hand, is not necessarily indicated in the data. For 2 years following the last disturbance, shrub crown increased at a greater rate where disturbance had occurred. However, changes in shrub crown were virtually identical on disturbed and undisturbed transects between 1971 and 1973 and it appears that further recovery cannot be predicted.

Vegetal Cover

Superficially, the percentage vegetal cover at ground level was not greatly influenced by management disturbances (fig. 3). To the degree that 110 plots on 11 transects are representative of the total burn, the data indicate about 4 percent vegetal cover in the first growing season, rising to 30 percent in 3 years, and 50 percent at 6 years. Then, following a 4-year rise to 58 percent, vegetal cover declined by 8 percent (table 6) as a result of a decline in seeded grasses. A more complete discussion of the fate of these species will be presented later.

Table 6.--[illegible]

Source	Succession Year											
	1	2	3	4	5	6	7	8	9	10	11	12
All vegetation under 18 inches	4.1	17.7	31.8	35.7	44.5	50.5	--	53.2		58.2		50.8
Vascular vegetation	4.1	16.1	23.9	28.4	29.6	36.1	--	38.2		38.0		27.1
Undisturbed	0.6	5.6	10.6	16.3	21.3	28.1		[illegible]		32.5		28.1
Disturbed	6.1	22.1	31.4	35.4	34.3	40.7	--	43.2	-	41.1		26.4
Introduced species	2.7	9.0	10.6	12.0	12.6	11.		18.5		17.3		4.7
[illegible]	0.9	3.0	4.3	7.0	8.3	8.9		8.6	--	8.6		1.8
Festuca ovina	0.5	2.1	2.6	2.0	2.2	2.9	--	[illegible]		2.9		2.0
Phleum pratense	0.6	2.1	3.0	2.5	1.7	1.9	--	1.8		1.3		0.7
Bromus inermis	0.2	1.0	[illegible]	0.5	0.5	0.9	--	0.9		0.6		[illegible]
Secale cereale	0.5	0.5	0.1	-	-	--	-					--
[illegible]	0.1	0.3	0.1	--	--	--	--	-		-		-
Native species	1.4	7.1	13.3	16.1	17.3	21.6		24.4		24.7		22.3
[illegible]	0.2	0.9	1.9	2.3	2.5	3.9		5.2		5.1		4.4
Undisturbed	0.3	0.7	2.2	3.4	4.4	6.8	-	6.4		[illegible]		[illegible]
Disturbed	0.1	1.0	1.8	1.7	1.4	[illegible]	-	1.3		1.8		1.4
Lupinus sulphureus	0.6	0.9	2.0	3.6	2.9	3.4	--	2.5	-	1.1		0.4
[illegible]	0.1	0.5	[illegible]	1.2	1.3	1.4	--	1.5		[illegible]		2.7
Calamagrostis rubescens	0.1	0.7	1.3	1.3	1.3	2.1	--	3.1		3.7		4.2
Epilobium angustifolium	0.1	0.3	0.7	0.7	0.7	0.5	--	0.4	--	0.5	--	0.2
Carex spp.	0.1	0.5	[illegible]	0.9	0.8	1.4	-	2.0		[illegible]	-	2.0

Closer examination of the data suggests that while total vegetal cover was not influenced, treatments may have substantially modified the structure of this vegetation layer. On the four transects considered to be undisturbed, vascular vegetation made up 90 percent of all low vegetal cover until dropping to 85 percent in the final year of study. By contrast, mosses and lichens became a progressively important component of cover on the disturbed transects until they exceeded 50 percent in the final year. Because the sampling system identifies bryophyte cover only when not overtopped by vascular vegetation, it cannot be shown that mosses and lichens were increased by treatments. It is suggested, however, that vascular cover was significantly reduced.

In the period prior to 1966, those transects eventually disturbed averaged more than twice as much vascular cover as the undisturbed transects. However, during the 4 years of management activity, vascular development was much slower on disturbed areas, and by 1973 the amount of vascular cover was nearly identical for treated and untreated areas. During the same time period, the ratio of shrub-forb cover to graminoids and conifers increased from 0.63 to 1.10 on undisturbed areas and dropped from 0.54 to 0.43 on treated areas.

If it is assumed that low cover should have been at least 85 percent vascular, or that vascular cover should have been at least half forbs and shrubs, the minimum calculated deficit on treated transects can be estimated between 11 and 25 percent cover. Again, it is not possible to judge the long-range significance of this reduction. However, there was no indication of recovery on any treated transect, and there is evidence that at least two plant species were substantially reduced as a result of treatments.

In attempting to examine the fate of individual species and their contributions to total cover (table 6), it was necessary to proportion cover estimates on the basis of recorded frequencies. Thus, if 15 percent vascular cover was recorded on 10 plots and 5 percent was identified as *Dactylus glomerata*, the remaining 10 percent was divided among other species according to their frequencies of occurrence. This calculation probably overestimates grass cover and underestimates forbs and small shrubs, but the general trends are considered adequate to evaluate species performance. The reader should also be aware that the averages for 11 transects presented in table 6 are lower than values actually recorded because, although some species were detected on all 11 transects, good development was usually confined to about half the samples.

Vaccinium scoparium was the most ubiquitous of the native low cover species on the burn. It was recorded with at least 0.7 percent cover on all transects and exceeded 25 percent on SC01. However, at least five transects received enough herbicide to produce major declines in *V. scoparium* cover. On the four undisturbed transects, vaccinium cover climbed steadily from 2 percent in 1964 to 7 percent in 1967 and 10 percent in 1973. By contrast, the seven disturbed transects also had 2 percent *V. scoparium* cover in 1964, but the species never exceeded 6 percent on any treated transect and the average for 1973 was only 1.4 percent.

Lupinus sulphureus was detected on eight transects but was of importance on only three. However, this legume species was very drastically reduced by herbicides. After providing cover in excess of 12 percent where it occurred and over 3 percent in all samples, it disappeared from two transects, dropped from 18 to 4 percent on the third transect, and made up less than 0.5 percent of all cover at the termination of the study.

Beargrass (*Xerophyllum tenax*) was detected on all 11 transects, but developed as an important cover component on only 5. On these five transects, beargrass cover was 2 percent in 1962 and nearly 6 percent by 1973. Development for this species was very consistent and appeared to take place independent of moisture conditions or herbicide effects.

Pinegrass (*Calamagrostis rubescens*) is usually considered an important component of the forest communities represented in the Sleeping Child burn. However, the species was recorded consistently on only 4 of 11 transects. The pattern of development is extremely interesting in that pinegrass cover rose from 0.3 to 2.0 to 3.5 percent in the first 3 years, remained at 3.5 percent for 2 years, and then climbed steadily to 11.6 percent in the 12th year. I assume that this pattern represents initial expansion via rhizomes, seed production for several years, and then a resumption of expansion via rhizomes of new plants developed from seed.

Fireweed (*Epilobium angustifolium*) produced some cover on every transect during the course of this study. However, only one transect had fireweed cover in every sample year of the study and the general patterns on different transects appear to suggest a 4- to 5-year cycle with local peaks around 2 percent and an average for the burned area of less than 1 percent fireweed cover.

Three species of carex were recorded in sample plots, and although all three apparently developed better at or above 7,000 feet, the only apparent difference among species was a suggestion that *Carex geyeri* grows earlier in the spring and is either more tolerant of moisture deficits or more responsive to excess moisture in April than *C. rossii*. In years when both April and May were dry (1966 and 1973), cover of *C. geyeri* increased while *C. rossii* was decreasing. Moisture excesses in April (1965 and 1967) resulted in proportionately greater cover increases for *C. geyeri*, while an April deficit followed by May moisture (1969) resulted in increases of *C. rossii*. Total cover for carex was about equally divided between these two species, with *C. concinnoides* appearing only on SC10 at less than 1 percent. The combined average for 11 transects shows carex stabilized at 1 percent in 1964, rising to 1.4 percent in 1967 and then stabilizing at 2.0 percent in 1969.

Aerial Seeding

Of the management activities recorded on the Sleeping Child burn, the aerial seeding operation in 1962 was the only treatment for which no treated-untreated comparison can be made. Moreover, because no watershed studies were conducted on the burn, a direct evaluation of watershed protection is not feasible. Nevertheless, the seeded species were an important component of vascular cover during most of this study and their performance is of interest for several reasons. During the first growing season (table 6), two-thirds of all cover on the burn was produced by seeded species, and in the 12th season the failure of these species resulted in a substantial decline of vascular cover.

Of the six aerially seeded species, two had virtually disappeared by the fourth growing season. The annual rye grass (*Secale cereale*) provided slightly more than 1 percent cover on five transects below 6,800 feet in 1962 and was apparently able to produce a seed crop in 1963. However, 1963 was dry during April and May; and although 1 percent cover was again produced, the seed crop was very poor. Rye grass cover dropped to 0.1 percent in 1964 and the species virtually disappeared thereafter. *Trifolium repens* simply never succeeded. Although the species was recorded in 10 percent of all plots in the first year, it was effectively limited to three transects below 6,800 feet on which it briefly produced about 1 percent cover.

The four perennial grasses were more successful. Orchardgrass (*Dactylis glomerata*), in particular, produced over one-fourth of all vascular cover on the burn in 1966. This species increased from 1 percent cover in the first growing season to 8.9 percent through years 6 to 10. However, 2 dry years in a row and the development of native vegetation apparently resulted in a drastic decline to less than 2 percent cover in 1973. Sheep fescue (*Festuca ovina* var. *durescula*), on the other hand, has performed at a lower but more consistent level by producing 2 percent cover in the second growing season and continuing at that level throughout the study.

Timothy (*Phleum pratense*) also produced cover in the 2 to 3 percent range but dropped below 2 percent in 1966 and has continued to decline to less than 1 percent in 1973. The least successful of the perennial grasses was apparently smooth brome (*Bromus inermis*), which contributed 1 percent cover in the second year and remained below that level for the rest of the study.

For at least 10 years, then, aerially seeded domestic grasses contributed significantly to ground-level cover on the Sleeping Child burn. Increases from 3 to nearly 15 percent cover recorded during the first 6 years were followed by declines to less than 5 percent cover in the 12th year; but for most of this period one-half to one-third of all vascular cover on the burn was supplied by introduced species.

The contribution to total cover on the burned area suggests that seeded plants were strong competitors during the early stages of succession. The study reported here was not designed to detect whether such competition was great enough to influence development of native species, and I am accordingly indebted to Jack E. Schmautz, Henry C. Jacobs, and Don Williams[3] for the following information:

> During July 1962, tree seedling densities and cover by seeded grasses were tabulated on 80 quarter-milacre plots distributed in groups of 10 on north and south aspects with high and low grass cover. Plots were resampled in August and again in 1963 and 1964. The data show that during the single month in 1962 and annually for 2 years, tree-seedling attrition was greater where grass cover was high. For the 2 years of study, on plots with grass cover less than 1 percent, tree-seedling attrition was 6 percent annually on north aspects and 8 percent on south aspects. On plots where grass cover averaged 29 percent, seedling attrition was 31 percent on north aspects and 41 percent on south aspects. Seeded grasses significantly reduced survival of lodgepole pine seedlings on the Sleeping Child Burn.

Overall, the aerial seeding effort can be considered at least partially successful--but primarily for reasons other than those originally intended. Orchardgrass, chewing fescue, and timothy can be credited with major contributions to herbaceous cover on the burned area; but the fact remains that total cover was under 5 percent in the first year and only 18 percent in the second. During that period, the soil surface was vulnerable and protection may have been minimal by any standard. On the other hand, some reductions in lodgepole pine densities were achieved even though the residual stocking was still far in excess of acceptable timber management goals. And, finally, the 10 to 13 percent grass cover for a period of at least 8 years was the major component of a transitory range grazed by about 600 cattle each summer.

Ecological Effects of Treatments

Although I have attempted to evaluate treatment effects by comparing disturbed and undisturbed transects, it is relatively obvious that the two groups do not provide a completely valid comparison. Only one of the undisturbed transects had tree densities approaching those on the treated areas; and, despite treatments that substantially reduced all forms of vegetation, the disturbed transects still averaged five times as many trees, three to six times as much shrub crown, and about twice as much vegetal cover as the undisturbed areas. Thus, even the most extreme deviation caused by treatments is probably within the range of normal variation for these high-altitude forest communities.

---

[3]Northern Region, USDA Forest Service, Missoula. Data compiled by the Division of Range Management.

A minimum evaluation of treatments, then, would suggest no effect at all. This, n fact, appeared to be the case with respect to trees. There were several major eductions in tree-seedling density following pole sales and herbicide applications, ut competition among seedlings could have been expected to produce substantial losses n these dense stands independent of outside influences. Examination of long-term ttrition rates suggests that the primary effect of management treatments may have imply been short-term acceleration of an attrition that would have occurred anyway.

At the shrub level, an assumption that treatments had no effect seems less valid. ailure of the shrub component of treated forest communities to completely recover does ppear to be a long-term adverse effect. Even though few shrubs were actually killed, ecovery is not necessarily predicted because the trees are now tall enough to prevent ull development of any species that is not shade tolerant. And, although most of he species involved are, in fact, relatively tolerant, the shrub component of treated orest communities is likely to remain below potential for a considerable period of ime.

Reductions in vascular plant cover also appeared to represent a long-term adverse ffect. Wherever disturbances occurred, vascular plant cover declined and a greater roportion of bryophyte cover was exposed. While this does not necessarily indicate hat community structure and watershed protection have been permanently compromised, he existing plant communities are certainly more primitive and less productive than ntreated communities would have been. Moreover, the loss or decline of several ascular plant species has, on some areas, resulted in less complex and presumably ess stable biological communities. None of the Sleeping Child plant communities were rticularly complex to begin with, and it is suggested that their ability to assimilate rther disturbance may have been diminished.

Ecologically, the introduction of domestic grasses to the Sleeping Child plant ommunities had both positive and negative aspects. The increase in species diversity, rticularly by plants resistant to herbicides, probably prevented even greater losses f vascular cover than those recorded. Also, the presence of any vegetation that abilizes soluble nutrients on site must be considered an asset. Concurrently, however, ditional competition from seeded species may have reduced the growth rate for native ecies as it did for trees and thereby prevented full development of cover by native ecies. In the long run, because introduced species have already declined from more an 50 to less than 20 percent in the total vascular cover and are apparently unable t compete with native perennials in dry summers, their eventual disappearance is redicted.

In an overall evaluation of the effects of management activity on the Sleeping Child plant communities, two points stand out. First, the various treatments applied dd cause major modifications in plant community structure. The herbicide applications, i particular, resulted in substantial losses of shrub-crown and vascular cover. Dspite these losses, however, the communities that have developed are not considered aypical. Second, the existing vegetation provides an impressive demonstration of asimilative capacity in plant communities that have remarkably low diversity.

INDEPENDENT VEGETAL TRENDS

Although herbicides and other treatments changed vegetation on some transects, there were also fluctuations that appeared to occur independent of treatment. Summaries of vegetation change for all transects, without reference to treatments, demonstrate a consistency of pattern that provides a useful insight into early seral successional trends and plant responses to natural factors of environment.

Shrubs

Annual changes in shrub volume, particularly in years with no management activity on the burn, were of special interest. In 1966 and 1973, for example, shrub volumes declined on most transects irrespective of location or treatment.

In an attempt to determine possible causes for these fluctuations, precipitation records for Darby, Montana, were examined for April through July of 1961 to 1973. Darby is located 14 miles west of the burn and 3,000 feet lower, but weather patterns are considered comparable even though actual precipitation at Darby is probably less than half that on the Rye Creek divide.

Precipitation at Darby averages just over 13 inches annually with a monthly distribution that is surprisingly regular. Only July and August average less than 1 inch of rainfall, and these dry months are preceded by 2 months averaging greater than 1.75 inches. Winter precipitation exceeds 1.50 inches only in November and December.

Despite the long-term regularity, Darby weather records show that local precipitation can vary considerably from year to year. Deviations from averages in excess of 0.5 inch per month appear to occur more than 50 percent of the time during the April to July season (table 7). Thus, plant growth, and particularly anthesis, could be substantially modified by deviations from average rainfall during the period of active growth and flowering.

Table 7.--*Deviation from long-term averages, precipitation at Darby, Montana, April through July, 1961 to 1973*

Year	Succession year	April	May	June	July
1961		0.43	0.00	-1.16	-0.59
1962	1	.17	.09	- .52	- .24
1963	2	- .18	- .88	1.49	- .71
1964	3	.71	.20	1.47	.15
1965	4	.66	- .65	.84	- .25
1966	5	- .69	- .88	.11	- .65
1967	6	.83	.71	.95	- .33
1968	7	- .27	- .97	- .30	- .53
1969	8	- .57	.83	- .33	- .34
1970	9	.09	.14	.61	2.11
1971	10	1.08	1.45	- .79	- .82
1972	11	- .50	- .91	- .52	- .60
1973	12	- .76	-1.18	- .27	- .47

In the relatively simple plant communities on the Sleeping Child burn there were only seven shrub species for which enough plants were recorded to constitute a major population on at least one transect. However, five of these species were recorded on no more than three transects and when exceptions due to disturbance are eliminated the samples are considered too small for analysis. Thus, there were only two shrub species for which the combined data from all transects could be examined.

Spiraea

Response of *Spiraea betulifolia* to fluctuations in precipitation is probably more pronounced than response of any other plant species (fig. 7). The bloom on spiraea is terminal and with our sampling technique usually adds 1 to 3 inches to plant height. Failure to bloom thus results in a shorter plant and a substantial loss of crown volume even if the plant remains otherwise healthy.

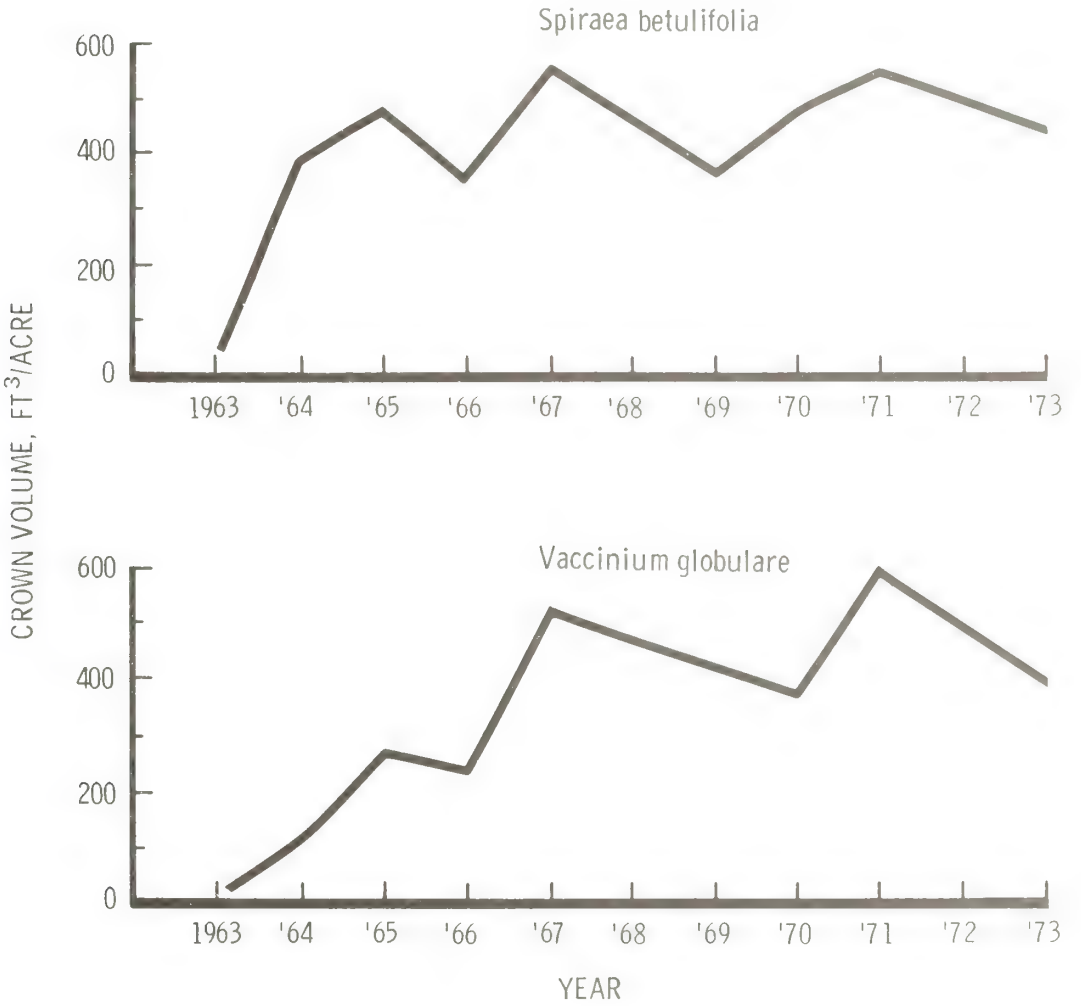


Figure 7.--Annual changes in average crown volume per acre, Spiraea betulifolia and Vaccinium globulare.

For the first two growing seasons after the fire, spiraea averaged less than 6 inches in height and was barely detected in the samples. In the next 2 years, growth was strong and volume increases substantial. In both years, this pattern corresponds to above-average precipitation in April. The dry May in 1965 apparently did not prevent successful growth initiated by moisture available in April.

Succession year 5 (1966) was dry, year 6 was wet, and the general growth pattern for spiraea was a decline followed by an increase. Years 7 and 8 were dry during April, and spiraea response was again a consistent decline. Moreover, the above-average moisture in May 1969 was apparently inadequate to reverse the volume decline initiated in April.

Years 9 and 10 were, respectively, moist and extremely wet during April and May; and spiraea crown volumes increased substantially during the 2-year period. Finally, the last 2 years of study had below-average precipitation and declines in spiraea crown volume were recorded throughout the burn.

In summary, fluctuations in crown volume for *Spiraea betulifolia* are highly correlated with moisture availability. April is probably the critical month in determining spiraea growth patterns. Inadequate moisture during May will not prevent spiraea anthesis initiated by April moisture; and precipitation in May will not reverse poor growth if April was dry.

Vaccinium

Responses of *Vaccinium globulare* to variations in annual moisture were similar to responses of spiraea (fig. 7), except that vaccinium had a greater tolerance to moisture deficits and exhibited greater response to excess moisture. Again, April moisture appeared to be critical. The single exception to vaccinium changes corresponding to April moisture occurred in 1970 when the effects of herbicides depressed vaccinium crown-volume averages even though an increase might have been predicted.

Species Frequencies

The plant communities on the Sleeping Child burn are relatively simple. Even the most complex transects produced fewer than 20 species in the ten 2- by 2-foot sample plots, and there was no study site on which 40 species were recorded as present. Transects averaged 9.3 species 1 year after the fire. Five additional species (14.1) were recorded on an average transect by the eighth growing season, and for the last 4 years of study the average was 13.0 species per transect.

A few plant species did occur on enough transects to justify examination, but the general paucity of vegetation suggests that combining species into broad plant groups might provide a better evaluation of long-term trends. Table 8 expresses the average combined frequency of occurrence for eight major plant groups on 11 transects as the probability of finding a representative of the group in a random sample plot. The effects of high frequencies for several species in a group are evident in the "introduced-grasses" category with the probability that more than one species representative will be found in a single plot. These data are also graphed in figure 8.

These frequency data indicate several significant trends. All plant groups had stabilized by the fourth postfire growing season and only the native-graminoids category increased after that time. This pattern is consistent with the hypothesis that community composition is determined in the first few years of seral development. Increases in native graminoids were primarily due to rhizomatous growth of pinegrass and two species of carex.

Table 8.--*Probabilities of occurrence in sample plots for eight plant groups on the Sleeping Child burn, 1962 to 1973*

Plant group	Succession year										
	1	2	3	4	5	6	7	8	9	10	11	12
Trees	0.45	0.52	0.53	0.52	0.54	0.55	--	0.53	--	0.38	--	0.34
Shrubs	.20	.56	.85	.92	.96	.94	--	.92	--	.91	--	.98
Native graminoids	.17	.28	.37	.42	.40	.42	--	.55	--	.58	--	.67
Introduced grasses	1.53	1.95	1.98	1.91	2.02	2.07	--	1.95	--	1.72	--	1.36
Native forbs	.25	.35	.61	.67	.65	.72	--	.67	--	.71	--	.69
Introduced forbs	.10	.05	.02	--	--	--	--	.01	--	.01	--	.01
Native annuals	--	.02	.06	.04	.06	.07	--	.06	--	.08	--	.09
Introduced annuals	.52	.07	.01	--	--	--	--	.01	--	--	--	--

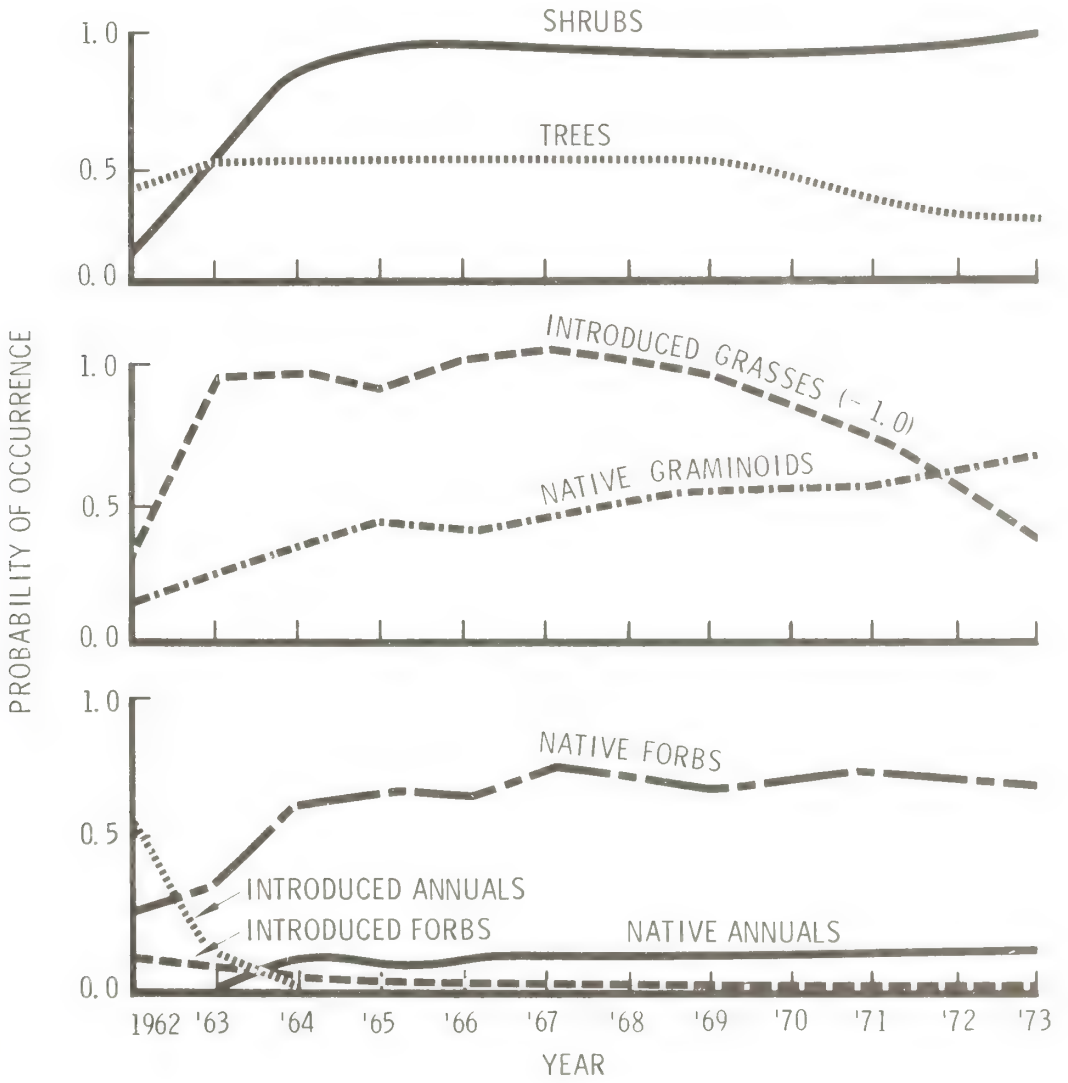


Figure 8.--Probabilities of occurrence in sample plots for eight plant groups on the Sleeping Child burn, 1962 to 1973.

Although tree densities did drop during the study, the decline in tree frequencies after the eighth year is probably a sampling artifact related to the height limit for woody vegetation. Once a tree reached 18 inches, it was no longer counted in the frequency plots. Although the same artifact would eventually appear in shrub samples, it has not because the majority of shrubs on the Sleeping Child burn were less than 1 foot tall even after 12 growing seasons.

Comparison of the frequencies for introduced and native graminoids reveals that the introduced species were relatively successful but are now on the way to becoming less important in the plant community. While graminoids have increased consistently since the burn, the introduced species began to decline in frequency after 1967.

In a somewhat similar pattern, native forbs and annuals have had constant or slightly increasing frequencies throughout this study, while introduced forbs and annuals have virtually disappeared. Most of this change is associated with the Dutch white clover (*Trifolium repens*) and annual rye (*Secale cereale*), which were seeded for watershed rehabilitation.

SUMMARY AND CONCLUSIONS

In the year following the 1961 Sleeping Child forest fire, 12 permanent transects ere established within the burned area to provide the basis for a long-term study of ostfire vegetal succession. Eleven transects were sampled annually through 1967 and emiannually through 1973. Data collected included tree density; shrub-crown volume; nd cover and frequency of occurrence for herbaceous and low woody species.

During the 12 years of study, all but two transects were disturbed in one or more ays by management activities; and by 1973 only four transects were considered to have eveloped nearly normally. However, even though the original study objectives had been ompromised, the available data do represent a series of case studies summarizing the evelopment of vegetation following wildfire and modified by the apparent effects of uperimposed management activities.

Management programs on the Sleeping Child burn have included a wide variety of reatments intended to prevent watershed deterioration, salvage wood fiber, reduce ree-seedling densities, and relieve grazing pressure on other parts of the Bitterroot ational Forest. Chemical thinning of tree seedlings, and to a lesser extent, pole ales and cattle grazing had marked effects on individual transects, but there was also discernible pattern of vegetal development independent of treatment effects.

Tree-seedling densities averaged more than 34,000 per acre in the first few years ollowing the Sleeping Child fire, but by the 12th growing season, the average tree ensity had dropped below 18,000 per acre. The survival rate on seven treated and four ntreated transects was nearly identical, however, and the data suggest that the pro- ortion of dominant trees was determined by competition among seedlings rather than the reatments applied.

Shrub-crown volumes averaged 2,076 ft^3/acre on 11 transects in 1973, but 7 tran- ects suffered substantial reductions, mostly as a result of herbicide applications. rown dieback was concentrated in alder, *Vaccinium globulare* and spiraea; and while here is little evidence that the plants affected were permanently removed from the orest community, there is also little evidence that shrub-crown deficits will ever be ecovered.

Average vegetal cover on all transects reached nearly 60 percent by the 10th post- re year, but treatments substantially modified the structure of this low vegetation y reducing the proportion of total cover represented by vascular plants. *Vaccinium oparium* and *Lupinus sulphureus*, in particular, were very adversely affected by erbicide applications.

Vegetal cover on the Sleeping Child burn was only 4 percent in the first season, t two-thirds of this cover was produced by introduced species. Annual rye grass and tch white clover had virtually disappeared by the second year, and smooth brome per- rmed very sporadically; but orchardgrass, chewing fescue, and timothy contributed 30

to 50 percent of the low vascular cover on the burn for at least 8 years. Eventual dominance by native species is suggested by the decline of introduced species to less than 5 percent cover in 1973.

Plant community structure was modified by management activities, but none of the existing Sleeping Child forest communities are considered completely atypical. Despite the remarkably low level of biological diversity, these high-altitude communities appear to have a high capacity to assimilate disturbance.

For two shrub species, *Spiraea betulifolia* and *Vaccinium globulare*, data are adequate to suggest a relatively strong year-to-year response in growth associated with spring moisture conditions. Spiraea, in particular, appeared to respond to April moisture; vaccinium was responsive to any spring moisture and tolerant of moisture deficits

Long-term trends in species frequencies indicate a relatively early stabilization of plant community composition following fire. Introduced forbs and annuals disappeare within 2 years and only the graminoids showed substantial changes in frequency after the fourth postfire growing season. In general, native species were still increasing in the 12th year while introduced grasses were disappearing.

☆ U.S.GOVERNMENT PRINTING OFFICE:1976-O-677-328/59

Lyon, L. Jack

1976. Vegetal development on the Sleeping Child burn in western Montana, 1961 to 1973. USDA For. Serv. Res. Pap. INT-184, 24 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

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Major modifications in plant community structure resulted from management activities, but none of the existing communities are considered completely atypical.

OXFORD: 45, 414.4, 435.1, 181.43, 182.21.
KEYWORDS: fire, forest succession, herbicide side effects.

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GROWING
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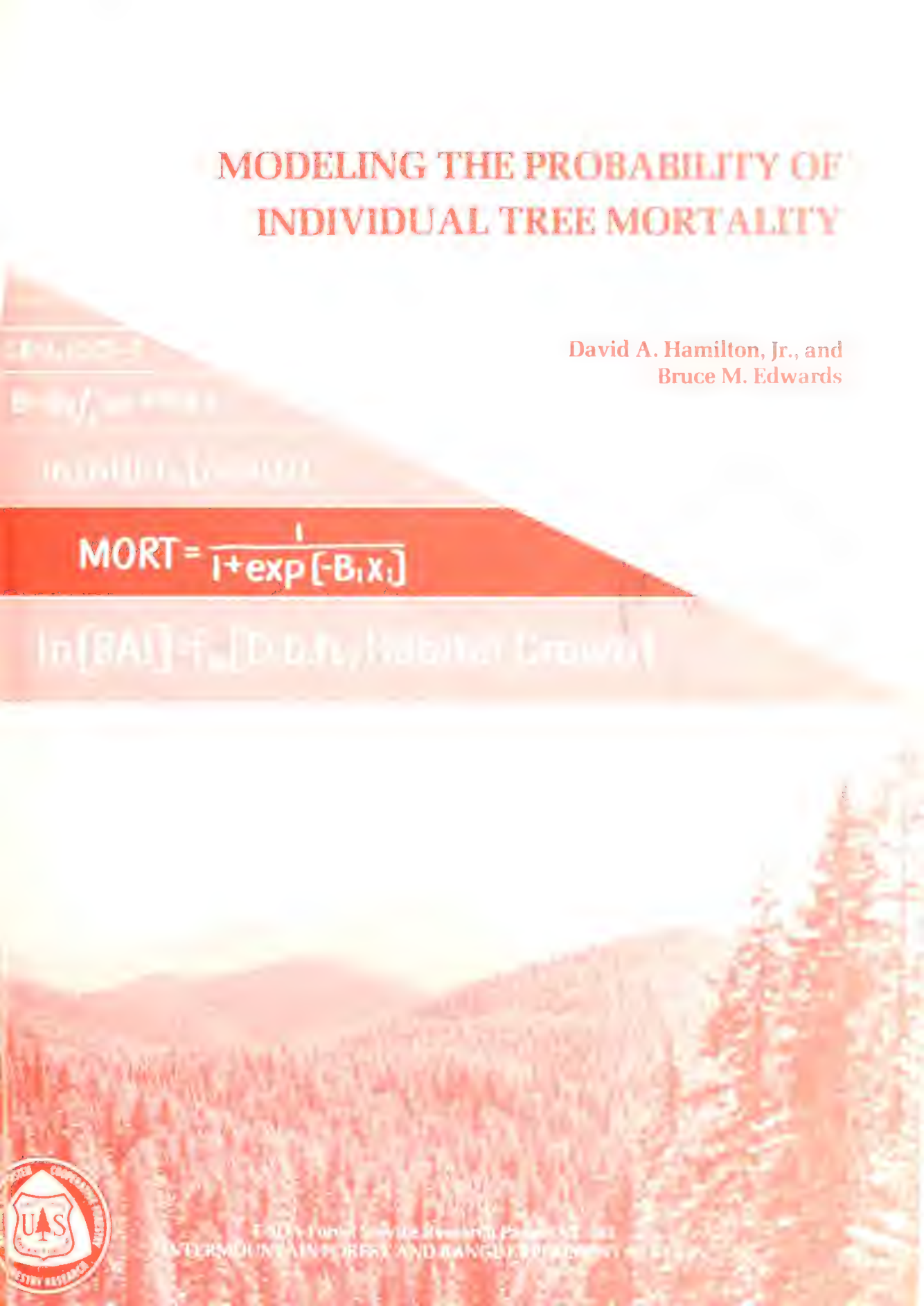
MODELING THE PROBABILITY OF INDIVIDUAL TREE MORTALITY

David A. Hamilton, Jr., and
Bruce M. Edwards

$$MORT = \frac{1}{1+\exp[-B_i X_j]}$$



INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

THE AUTHORS

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Forest Service
U.S. Department of Agriculture
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ABSTRACT

This paper describes procedures for developing and testing models that predict the probability of individual tree mortality. The modeling procedures include data screening, parameter estimation, and model verification techniques that have been designed to deal with dichotomous dependent variables. To demonstrate the procedures, mortality models for 10 north Idaho species are developed and verified.

INTRODUCTION

Because mortality is an important component of stand development, models that predict mortality over time must be included in systems that project stand growth. The mortality models described in this paper were developed for a stand growth prognosis model devised by Stage (1973). Other stand growth models, such as those developed by Myers (1973), Lin[1], Stiell[2], and Bartos[3], also require some form of mortality model to deal with the mortality component of stand development.

The mortality model can be used to help schedule management activities. Stands of trees for which the model predicts high mortality rates should be considered high risk stands susceptible to insect and disease outbreaks and should be logged, salvaged, or otherwise treated before stands composed of trees with low predicted mortality rates.

Mortality models also reveal relationships that may provide a better understanding of how and why mortality occurs in a stand. This information is valuable in management planning and in developing strategies to control mortality.

The models discussed in this paper were developed by means of a three-step analysis. The first step is to screen the independent variables for those that show the strongest relationships to the probability of mortality. The variables selected as most significant by the screening algorithm are used as predictors of the probability of mortality in a logistic model. The regression coefficients for this model are then estimated by a nonlinear regression program, RISK (Hamilton 1974). The final step, model verification, employs a chi-square statistic to evaluate the accuracy with which the proposed model predicts the mortality that occurred on an independent data set.

---

[1]Lin, Jim Y. 1973. Stand growth simulation models for Douglas-fir and western hemlock in the northwestern United States. Paper presented at Joint Meeting of Subject Groups S4.01 and S6.02, Int. Union For. Res. Organ., Vancouver, B.C., Can., Aug. 20-24, 1973.

[2]Stiell, W. M. 1973. An application of stand volume and tree mortality models in yield table construction. Paper presented at Joint Meeting of Subject Groups S4.01 and S6.02, Int. Union For. Res. Organ., Vancouver, B.C., Can., Aug. 20-24, 1973.

[3]Bartos, Dale L. 1973. A dynamic model of aspen succession. Paper presented at Joint Meeting of Subject Groups S4.01 and S6.02, Int. Union For. Res. Organ., Vancouver, B.C., Can., Aug. 20-24, 1973.

PROPERTIES OF MORTALITY MODELS

Models can be developed to predict either stand mortality or the mortality of individual trees within the stand. The models discussed in this paper were developed to predict individual tree mortality within a specified time interval as a function of stand and individual tree characteristics. The true probability of mortality is bounded by 0 and 1. Thus, it would be desirable for the mortality model to provide estimates of probability in the interval [0,1].

A linear regression model frequently has been used for this purpose. However, a linear model cannot insure that probability estimates will be in the interval [0,1]. In addition, using a linear regression model for this purpose creates many statistical problems (Hamilton 1974).

Walker and Duncan (1967) and Neter and Maynes (1970) have suggested that the logistic function, which limits estimates of probability to the interval [0,1], is the statistically preferred model for expressing the relationship between a 0,1 dependent variable and a set of independent variables. For this reason, we have used a logistic function for modeling mortality.

DATA REQUIREMENTS FOR MORTALITY MODELING

Large quantities of individual tree data must be available to fit mortality models that predict the probability of an individual tree dying within a specified interval. Individual tree characteristics on sample trees must be measured at the beginning of the interval. The status of the tree, that is, whether it is alive or dead, must be recorded at the end of the interval.

Mortality models from such data are directly applicable only for the interval and geographic area actually measured. We extend model capability by distributing plots over the geographic range of interest and by measuring them over several successive intervals. Variability in mortality rates that is caused by uncontrollable climatic factors may be accounted for in two ways. Plots may be measured at intervals of at least 5 to 10 years in order to include a range of climatic conditions within the measurement interval. Alternatively, plots may be remeasured at shorter intervals. For example, we could measure trees annually for 10 to 20 years and record mortality when it occurs. When this is done, variability in mortality rates caused by climatic variation is accounted for by the fact that a range of climatic conditions is represented in the data set used for modeling.

The time span required to gather data is often longer than we can afford; thus, we frequently work with available data. To do this, geographic range, distribution of sample trees, and time span must be representative of the target population. When this is not the case, we must recognize and state the limitations of the resulting models.

Models reported in this paper reflect processes or conditions in the forest at the time the data were collected. False mortality estimates may result when the equations are applied to trees growing under different conditions. For example, during the data gathering period mortality from white pine blister rust (*Cronartium ribicola*) and from the mountain pine beetle (*Dendroctonus monticolae*) were at epidemic levels. Thus, the mortality model reported in this paper will produce high levels of mortality in western white pine (*Pinus monticola*). Models for other species reported in this paper do not appear to produce abnormal mortality rates for the species involved. However, as the dynamics of the north Idaho forests change, the models will require continual updating.

Data Used in This Study

Data were collected over two periods on Potlatch Corporation permanent variable-radius plots, using a 25-factor prism. In the first measurement period (1964-1970), part of the data was measured over a 5-year interval and the remainder was measured over a 3-year interval. In the second measurement period (1968-1974), data were recorded over a 6-year interval.

MODELING METHODS

Data Screening

The first step is to screen the independent variables for those that best explain variations in the dependent variable (mortality rate).

In the model to be fit to the data, the dependent variable is dichotomous: the value 0 is assigned to green trees, the value 1 to dead trees. For model fitting, probability of mortality for an individual tree is not considered; a specific tree is either alive or dead. The analytical method enables us to use all trees with similar characteristics (independent variables) to estimate the probability of mortality for a tree with these characteristics.

In fitting the model, we assume that each tree is an independent observation. Thus, we ignore the fact that there is some clustering in the selection of sample trees However, in most instances the model will be applied to stands; thus, the impact of clustering, and of the resulting nonindependence of observations, is reduced.

The algorithm used in this screening process has been developed specifically for situations in which the dependent variable is dichotomous. SCREEN, the computer progra that does the screening, is described by Hamilton and Wendt (1975). The theoretical development of the algorithm and the statistic used for screening are discussed by Gleser and Collen (1972) and by Sterling and others (1969).

Data were divided into two parts: data screening and parameter estimation were done with data collected in the first measurement period; models were verified by means of data collected in the second measurement period.

Age, diameter breast high, height, crown class, basal area per acre of the stand, percent defect, and diameter growth rate prior to mortality were the variables in the data set which were considered potential predictors of mortality. Instructions for estimating percent defect as specified in "Instructions for Forest Inventory of Potlatch Forests, Inc. Logging Units" as revised July 8, 1959, are reproduced in the appendix. SCREEN was run independently for each of the 10 north Idaho species included in this study.

Output from SCREEN consists of a tree diagram showing characteristics that best predict mortality. SCREEN also reports how mortality rate changes over the range of these predictors.

We have considered three levels of significance: a high level (95 percent), a moderate level (75 percent), and a low level (50 percent). The objective of data screening is to identify combinations of independent variables that are related to the probability of mortality. By including the 75 and 50 percent significance levels, we were able to gain a better understanding of the relationships that exist between the probability of mortality and the set of independent variables. However, only independent variables significant at the 95 percent level were included in the models developed in this study.

An example of the use of SCREEN to develop tree mortality predictors for grand fir (*Abies grandis*) follows. The SCREEN output for this example is displayed in figure 1. At the 95 percent significance level two tree characteristics, percent defect and crown class, are significant predictors of tree mortality. The output indicates that grand fir trees with defect percent from 0 to 90 have a 5-year mortality rate of 81/1523 = 0.053, while trees with 91 to 100 percent defect have a mortality rate of 36/259 = 0.139. Additionally, among trees with percent defect of 0 to 90 percent, those with crown class of 1, 2, or 3 (dominant, codominant, intermediate) have a mortality rate of 58/1310 = 0.044, while trees with crown class 4 (suppressed) have a mortality rate of 23/213 = 0.108.

At the 75 percent significance level, the significant predictors are percent defect, crown class, diameter, and age. At the 50 percent significance level, the significant predictors are the same as the predictors at the 75 percent level of significance. This implies that only a negligible amount of the unexplained variation can be explained by any of the unused independent variables.

Parameter Estimation

Once the "optimal" set of independent variables has been selected, it is necessary to estimate the parameters of the mortality model. The general form of the logistic mortality model is

$$P = [1 + \exp[-(\beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots)]]^{-1}$$

where

P = probability of mortality in a specific time interval

β_i = ith nonlinear regression coefficient (model parameters), $i = 0,1,\ldots$

x_j = jth independent variable, $j = 1,2,\ldots$

Figure 1.-SCREEN output of potential mortality predictors for grand fir.

```
MORTALITY STUDY FOR GRAND FIR                    50% SIGNIFICANCE LEVEL

                                                      AGE OF TREE
                                                          1-2
                                                          3-5
                                                          6-8
                                    CROWN CLASS           9-12
                                        1                 ........
                                        2                 .000701.
                  % DEFECT              3                 .000039.
                      0-20              ........          ........
                      21-35             .001252.          13-19
                      36-50             .000058.          20+
                      51-60             ........          ........
                      61-70                               .000551.
                      71-80                               .000019.
                      81-90                               ........
                      ........
                      .001442.          4
KIND                  .000081.          ........
    LIVE              ........          .000190.
    DEAD                                .000023.
    ........                            ........
    .001665.
    .000117.
    ........                    DIAMETER
                                        0.0-3.0
                                        3.1-6.0
                                        6.1-9.0
                                        ........
                      91+               .000031.
                      ........          .000010.
                      .000223.          ........
                      .000036.          9.1-12.0
                      ........          12.1-15.
                                        15.1-18.
                                        18.1-30.
                                        30.1+
                                        ........
                                        .000192.
                                        .000026.
                                        ........
```

MORTALITY STUDY FOR GRAND FIR 75% SIGNIFICANCE LEVEL

KIND	% DEFECT	CROWN CLASS	AGE OF TREE	DIAMETER
LIVE	0-20	1	1-2	0.0-3.0
DEAD	21-35	2	3-5	3.1-6.0
.....	36-50	3	6-8	6.1-9.0
.001665.	51-60	.....	9-12	.....
.000117.	61-70	4	.....	91+
.....	71-80	.....	13-19	.....
	81-90	.000190.	20+	.000223.
	.....	.000023.	.....	.000036.
	.001442.	.....	.000551.	.....
	.000081.		.000019.	9.1-12.0
	.....		.....	12.1-15.
				15.1-18.
				18.1-30.
				30.1+
				.....
				.000192.
				.000026.
				.....

MORTALITY STUDY FOR GRAND FIR 95% SIGNIFICANCE LEVEL

KIND	% DEFECT	CROWN CLASS
LIVE	0-20	1
DEAD	21-35	2
.....	36-50	3
.001665.	51-60	.....
.000117.	61-70	.001252.
.....	71-80	.000058.
	81-90	.....
	.....	4
	.001442.	.....
	.000081.	.000190.
	.....	.000023.
		.....
	91+	
	.....	
	.000223.	
	.000036.	
	.....	

The RISK computer program (Hamilton 1974) is a nonlinear regression program that efficiently estimates the parameters. This program was used to estimate the β_i for those independent variables selected for inclusion in the model by the data screening procedure.

Because the sampling probability for each observation in the data set was proportional to $(DBH)^2$, each observation was assigned a weight proportional to the inverse of $(DBH)^2$ in RISK. To model annual mortality rates from a data set that included two unequal length time intervals, the dependent variable associated with each observation was divided by the appropriate time interval.

A model developed from data measured over a specific time interval produces mortality rate estimates that are applicable only to similar time intervals. This could be a severe limitation when we wish to predict the probability of mortality for a range of time intervals. The limitation can be partially overcome by considering mortality rate to behave like compound interest. The model can then be used to predict mortality for any measurement interval, and data sets with unequal remeasurement intervals can be used for model verification. Because we chose a 1-year base for this analysis, mortality functions from RISK will predict annual mortality rate.

In the following derivation, mortality rate is treated as a negative interest rate. The standard compound interest formula (1) may be used to calculate the number of surviving trees over any desired time interval.

$$V_n = V_o\ (1-r)^n \tag{1}$$

where

V_n = number of trees living after n years

V_o = number of trees living today

r = annual mortality rate

n = number of years in prediction interval.

This formula may be applied directly when the mortality rate is an annual rate. Algebraic manipulation of formula (1) produces the following formula that converts an annual mortality rate to an n-year mortality rate:

$$\frac{V_n}{V_o} = (1-r)^n$$

$$\therefore \quad \frac{V_o - V_n}{V_o} = 1-(1-r)^n$$

$$\therefore \quad P_n = 1-(1-r)^n \tag{2}$$

When the mortality rate is for a period of n years, the following formula, derived from equations (1) and (2), should be used to calculate mortality:

$$V_{n*} = V_o\ (1-P_n)^{n*/n} \tag{3}$$

where

V_{i,t^*} = number of trees living after n^* years

$V_{i,t}$ = number of trees living today

$P_{i,n}$ = mortality rate based on an n year interval

n = number of years used as basis for estimating $P_{i,n}$

n^* = number of years for which prediction is desired.

Algebraic manipulation of formula (3) produces the following formula that converts an n-year mortality rate to an n^*-year mortality rate:

$$\frac{V_{i,t^*}}{V_{i,t}} = (1-P_{i,n})^{n^*/n}$$

$$\frac{V_{i,t} - V_{i,t^*}}{V_{i,t}} = 1 - (1-P_{i,n})^{n^*/n}$$

$$P_{i,n^*} = 1-(1-P_{i,n})^{n^*/n} \qquad (4)$$

Continuing with the grand fir example, the mortality probability prediction model from RISK is as follows:

$$P_i = 1.0/\{1.0 + \exp[4.89819 - 0.0047554(\%DEF_i) - 0.222746(CC_i)]\}$$

where

$\hat{P}_i$ = predicted annual mortality rate for tree i

$\%DEF_i$ = percent defect in tree i

CC_i = crown class of tree i

In this model, the qualitative variable crown class is used as if it were a continuous variable. Because we would expect a constant increase in mortality rate as crown class changes from dominant to suppressed (1 to 4), using crown class in this manner should cause few problems.

This model predicts the probability that an individual grand fir tree will die in a given year as a function of percent defect and crown class. Thus, for codominant grand fir (CC_i = 2) with 25 percent defect, the probability of mortality in the following year is:

$\hat{P}_i$ = 1.0/{1.0 + exp[4.89819 - 0.0047554(25.0) - 0.222746(2)]}

= 1.0{1.0 + exp[4.89819 - 0.11888 - 0.44549]}

= 1.0/[1.0 + exp(4.33382)]

= 1.0/77.23494

= 0.01295

This tree would have a 1.29 percent chance of dying during a 1-year period. This yearly mortality rate will change as the tree parameters, percent defect and crown

class, change. As percent defect becomes greater, the probability of mortality increases. If the tree's crown class changes to a dominant position, its probability of mortality will decrease, while a change to an intermediate or suppressed crown class will increase its probability of mortality.

Model Verification

The models discussed must be verified before being employed to describe mortality in a stand over time. Verification tests whether the proposed model does more than reproduce peculiarities of a specific set of data.

"Goodness of fit" of the models was tested by means of the chi-square statistic

$$\chi^2 = \sum_{i=1}^{n} (O_i - E_i)^2 / E_i$$

where

O_i = observed number of mortality trees falling in the ith class

E_i = expected number of mortality trees falling in the ith class

n = number of classes

χ^2 = chi-square statistic

A computer program was written for verifying the proposed models with the chi-square statistic. The population is divided into twenty-one 2-inch diameter classes that range from 0-2 inches to >40 inches. The verification program uses the nonlinear regression model developed with the aid of RISK to predict the probability of mortality for each observation in the population being used for validation. Goodness of fit of the model is determined by using the chi-square statistic to compare the observed number of dead trees in each 2-inch diameter class with the expected (predicted) number of dead trees in the class.

The set of data for verifying the models from RISK has a remeasurement interval of 6 years. Thus, it was necessary to use the compound interest formula to convert the annual probability of mortality predicted by the model to the probability of mortality over the measurement interval.

The results of model verification of the grand fir model developed by RISK are presented in table 1. We will use line 3 of table 1 to explain the output. Class 3 contains all trees from 4 to 6 inches d.b.h. This class contains 73 trees (col. 4) or 4.74 percent (col. 3) of the population. The probability of mortality for each tree in the class is summed to obtain the expected number of trees that will die. Of the 73 trees in class 3, 7.2 trees (col. 6) are expected to die. Eight of these trees (col. 5) actually died. The chi-square statistic comparing these values is reported in column 7. The sum of the chi-square statistics for all diameter classes is the measure of goodness of fit for the model. At the 95 percent confidence level, the tabulated chi-square statistic for 21 degrees of freedom is 32.7. Since the calculated chi-square value of 26.73 is less than the tabulated value, we cannot reject the model at the 95 percent confidence level.

Table 1.--[illegible]

Class (1)	Interval (2)	Percentage in interval (3)	Number in interval (4)	Observed mortality (5)	Predicted mortality (6)	[illegible] (7)
1	0.00 - 2.00	1.69	26.0	3.0	2.6	0.06
2	2.00 - 4.00	4.55	70.0	5.0	6.9	0.52
3	4.00 - 6.00	4.74	73.0	8.0	7.2	0.09
4	6.00 - 8.00	6.50	100.0	10.0	9.7	0.01
5	8.00 - 10.00	7.73	119.0	7.0	10.5	1.17
6	10.00 - 12.00	6.82	105.0	3.0	9.1	4.09
7	12.00 - 14.00	7.41	114.0	5.0	9.8	2.35
8	14.00 - 16.00	6.95	107.0	7.0	8.4	0.23
9	16.00 - 18.00	5.39	83.0	7.0	6.2	0.10
10	18.00 - 20.00	6.24	96.0	3.0	7.6	2.78
11	20.00 - 22.00	5.00	77.0	2.0	6.1	2.76
12	22.00 - 24.00	5.13	79.0	8.0	6.0	0.67
13	24.00 - 26.00	4.09	63.0	7.0	4.8	1.01
14	26.00 - 28.00	4.35	67.0	7.0	5.2	0.62
15	28.00 - 30.00	4.94	76.0	5.0	5.7	0.09
16	30.00 - 32.00	5.00	77.0	8.0	6.0	0.67
17	32.00 - 34.00	3.96	61.0	9.0	4.7	3.93
18	34.00 - 36.00	2.66	41.0	3.0	3.2	0.01
19	36.00 - 38.00	1.82	28.0	1.0	2.2	0.65
20	38.00 - 40.00	2.27	35.0	6.0	2.9	3.31
21	40.00+	2.73	42.0	1.0	3.3	1.60
Total			1,539.0			26.73

MORTALITY PREDICTION FOR NORTH IDAHO SPECIES

Mortality prediction models were developed for five tree species in north Idaho. Models for western white pine, western larch (*Larix occidentalis*), Douglas-fir (*Pseudotsuga menziesii*), grand fir, and western redcedar (*Thuja plicata*) are reported in table 2. For each species, table 2 reports the prediction equation, the number of observations used in the analysis, and the means and standard deviations for diameter at breast height and for variables used in the prediction equations. The means and standard deviations of the variables are reported so users are aware of the limitations of the models and to enable users to select populations to which the models may be applied with confidence.

In table 3, annual mortality rates are reported for western hemlock (*Tsuga heterophylla*), lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and ponderosa pine (*Pinus ponderosa*) in north Idaho. Because of limited data and low mortality rates no significant predictors of mortality were found for these species; therefore, only annual mortality rates are reported for these five species. The number of observations, and the mean and standard deviation of the diameter distribution are reported for each species to indicate limitations of the data.

The "optimal" models for grand fir and western redcedar use the variables, crown class and percent defect. The variables are not available in the growth prognosis model (Stage 1973) in which these models are to be used. Further, percent defect frequently is not measured in forest surveys. Thus, the alternative models in table 4 were developed using more available independent variables.

Table 2.--*Mortality models for north Idaho species*

Species:	*Pinus monticola* (western white pine)	
Prediction equation:	$1/\{1+\exp[3.25309-0.00072647(BA)+0.0166089(DBH)]\}$	
No. of observations:	1,363	
Variable	*Mean*	*Standard deviation*
BA - basal area/acre (ft^2/acre)	235.0	100.0
DBH - diameter at breast height (inches)	23.1	10.4

Species:	*Larix occidentalis* (western larch)	
Prediction equation:	$1/\{1+\exp[3.8774+0.2177(DBH)-0.0002209(HT)-0.02409(AGE)]\}$	
No. of observations:	784	
Variable	*Mean*	*Standard deviation*
HT - height (feet)	122.1	33.1
AGE - age (total years)	129.1	41.8
DBH - diameter at breast height (inches)	19.5	8.5

Species:	*Pseudotsuga menziesii* (Douglas-fir)	
Prediction equation:	$1/\{1+\exp[4.78313+0.21186(DBH)-0.039527(HT)]\}$	
No. of observations:	2,036	
Variable	*Mean*	*Standard deviation*
DBH - diameter at breast height (inches)	16.3	8.6
HT - height (feet)	88.8	34.8

Species:	*Abies grandis* (grand fir)	
Prediction equation:	$1/\{1+\exp[4.89819-0.0047554(\%DEF)-0.222746(CC)]\}$	
No. of observations:	3,864	
Variable	*Mean*	*Standard deviation*
%DEF - percent defect (appendix)	26.2	35.5
CC - crown class (1,2,3,4)	1.6	1.3
Diameter at breast height (inches)	18.0	10.59

Species:	*Thuja plicata* (western redcedar)	
Prediction equation:	$1/\{1+\exp[5.99811-0.01037(\%DEF)-0.26124(CC)]\}$	
No. of observations:	3,282	
Variable	*Mean*	*Standard deviation*
CC - crown class (1,2,3,4)	1.7	1.4
%DEF - percent defect (appendix)	40.9	39.4
Diameter at breast height (inches)	24.7	16.1

Table 3.--*Mortality rates for north Idaho species (no significant independent variables)*

Species:	*Tsuga heterophylla* (western hemlock)	
Mortality rate:	0.01355/yr	
No. of observations:	255	
Variable	*Mean*	*Standard deviation*
Diameter at breast height (inches)	16.9	11.9
Species:	*Pinus contorta* (lodgepole pine)	
Mortality rate:	0.00631/yr	
No. of observations:	178	
Variable	*Mean*	*Standard deviation*
Diameter at breast height (inches)	9.9	4.3
Species:	*Picea engelmannii* (Engelmann spruce)	
Mortality rate:	0.01987/yr	
No. of observations:	325	
Variable	*Mean*	*Standard deviation*
Diameter at breast height (inches)	17.2	8.7
Species:	*Abies lasiocarpa* (subalpine fir)	
Mortality rate:	0.02571/yr	
No. of observations:	145	
Variable	*Mean*	*Standard deviation*
Diameter at breast height (inches)	13.9	6.2
Species:	*Pinus ponderosa* (ponderosa pine)	
Mortality rate:	0.00949/yr	
No. of observations:	254	
Variable	*Mean*	*Standard deviation*
Diameter at breast height (inches)	18.4	9.3

Table 4.--*Alternative mortality models for grand fir and western redcedar*

Species:	*Abies grandis* (grand fir)
Prediction equation:	$1/\{1+\exp[4.8690+0.009915(HT)-0.01417(BA)]\}$
Species:	*Thuja plicata* (western redcedar)
Prediction equation:	$1/\{1+\exp[3.3028+0.01899(HT)+0.01048(BA)]\}$

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APPENDIX

Instructions for Estimating Percent Defect
(reproduced from "Instructions for Forest Inventory of Potlatch Forests, Inc. Logging Units" as revised July 8, 1959)

INSTRUCTIONS FOR ESTIMATING DEFECT

Minimum Merchantable Cruising Standards

No green tree is to be considered to be a cull unless all logs in the tree, cruised separately on their own merits, are culls based on minimum Company scaling standards.

Minimum standards for logs of the mixed species is 1/2 of its gross volume must be merchantable; and for logs of the pine species, 1/3 of their gross volume must be merchantable for lumber. Individual logs of dead trees cruised for pulp content are considered merchantable if 50% of their gross volume is free of rot. Thus a tree, either green or dead, may be given a defect figure of 75% or even more if it has a log or two in it that barely meets minimum standards.

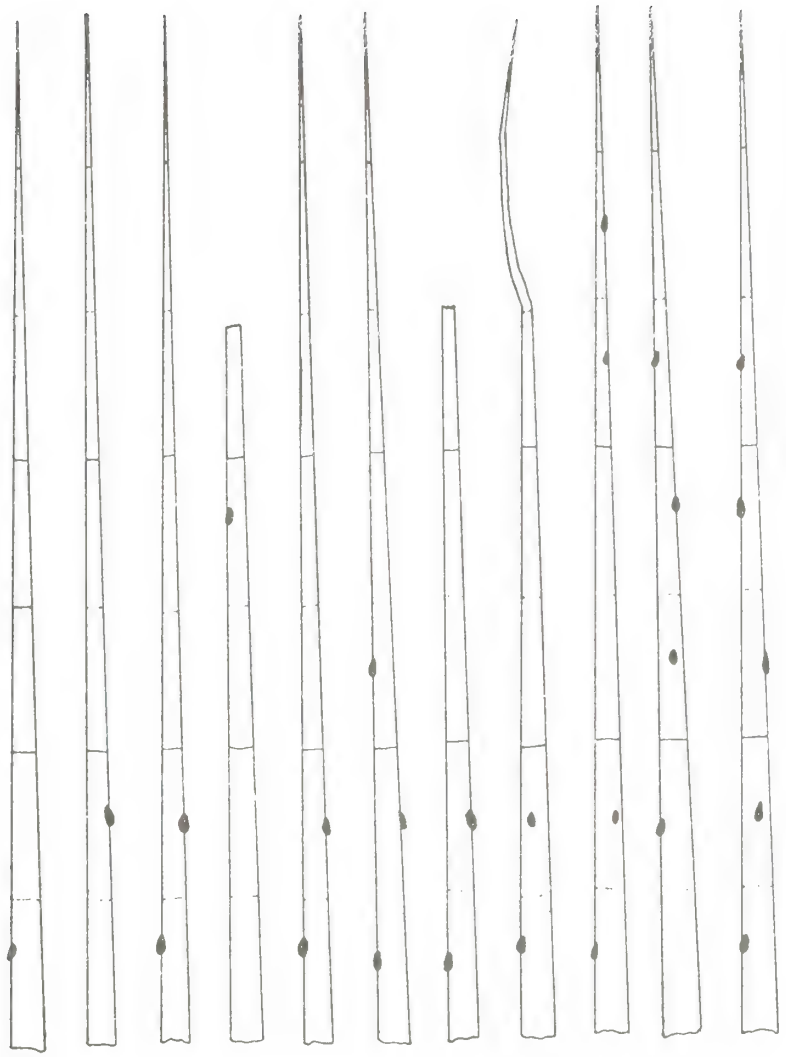
Dead Douglas-fir trees with few or no red needles, less than 22" DBH, will often be complete culls.

Sap-rotted trees - Reduce the diameter by 1/4 and the volume will be reduced by 1/2.

Minimum top diameters for white pine by DBH classes:

DBH	Top Dia.	DBH	Top Dia.	DBH	Top Dia.	DBH	Top Dia.
12	6	24	9	36	11	48	13
14	7	26	9	38	11	50	14
16	7	28	9	40	12	52	14
18	7	30	10	42	12	54	15
20	8	32	10	44	13		
22	8	34	11	46	13		

White Fir
A grandis



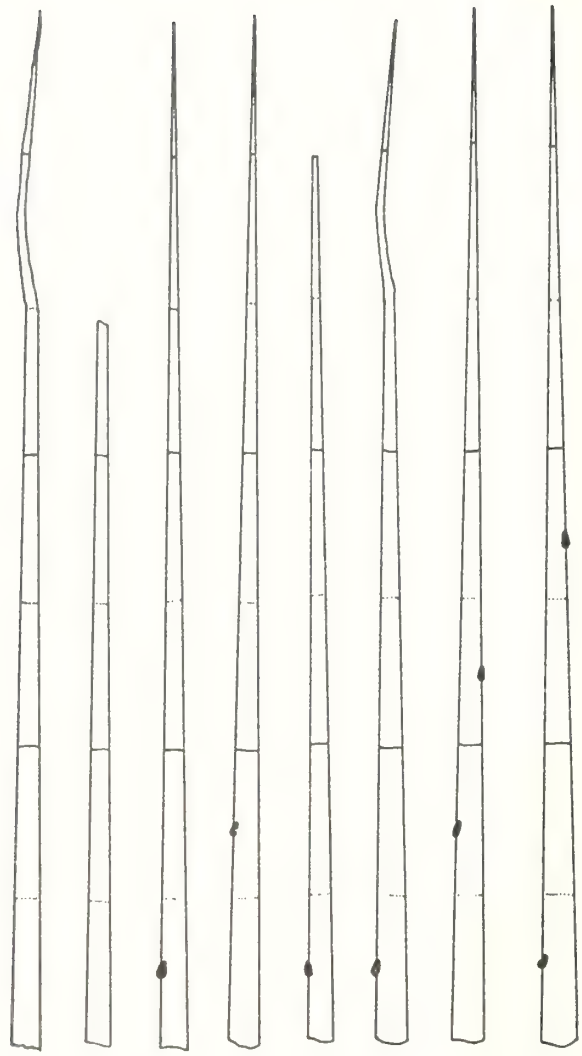
Average merchantable timber (6 logs). This roughly illustrates the % defect in 2nd growth white fir on average W.pine sites with regard to conk location. On white pine sites [illegible] timber, [illegible] conk (F. [illegible] torium) will cull [illegible] in a white fir tree.

25% 25% 50% 50% 50% 75% 75% 75% 75% 75% 100% - % defect (lumber)

General notes on white fir:

1. 2nd and 3rd logs are most apt to be infected.
2. 50% of the volume is in the first long log (roughly).
3. Size of conk indicates to some extent the age of infection.
4. Broken tops, cat faces and frost cracks are also serious indications of defect. The amount loss is indicated by the severity of the defect.
5. Appearance of bark sometimes gives indication of soundness of tree.

White fir A grandis



25% 25% 50% 75% 75% 75% 100% 100% - % defect (lumber)

This diagram shows the percent of lumber lost in white fir on all sites except white pine Sites I and II, and in over-mature timber on these good white pine sites, with regard to the fungus E. tinctorium.

1. If conk is on first log, cut 50% of tree volume.
2. If conk is on second or third log, cut 75% of tree volume.
3. If conk is on both second and third log, deduct 100%.
4. Rot extends 1 log below first visible conk and 1 log above last visible conk.

The above rules also apply to subalpine fir and western hemlock.

Western Red Cedar

Some average deductions for cedar:

Spike tops - 1-2 logs in old growth and 8' in 2nd growth.

Schoolmarms - 1-2 logs below fork in old growth. 8' in 2nd growth.

Knees - Indicate rot extends 1 log up and 1 log down from knee. (Generally joins other defect either above or below in tree.

Butt Rot - 1-2 logs in old growth. 8' in 2nd growth.

Defect in old-growth stand determined by:

A. Tree vigor as indicated by:
   1. Bark appearance
   2. Crown foliage (color & amount)
   3. Top (dead spike or alive)
   4. Limbs - cluster of dead ones in green crown.

B. Hollow Butts - These may be determined by sounding with ax, or seen through open cracks.

C. Schoolmarm tops & deformed trunks.

D. Cat faces (Fire Scars).

Defect in second-growth stand determined by:

A. Hollow Butts - Defect usually plays out in about 8'. Sometimes takes whole tree if tree vigor is unusually poor.

B. Schoolmarm tops, deformed trunks, spike tops. Deduct from 8' to 2 logs, rarely whole tree.

C. Cat faces, defect generally plays out within a few feet of exterior sign. If a cedar is vigorous, it will outgrow a cat face quicker and with less loss than our other species.

Notes on Cedar, T. plicata

Best old-growth cedar found on good, moist, well-drained sites. Rot is greatest on trees occupying low, flat, poorly-drained sites. The age of the trees is also an important factor regarding rot.

Old-growth climax stands are nearly always heavily infected with Poria weirii (yellow laminated rot). The fruiting body is located near root collar and is very hard to detect. Because conks are difficult to detect, rules for deductions on this basis cannot be made for cedar. This rot often causes the hollow butts of cedar, often runs into the second log and sometimes extends throughout the tree. So severe are the losses, caused largely by this fungus, that some climax stands (over mature) have been found to be about 65% defective on the stump.

Rot, in old-growth cedar that is forked within 30' of the butt, nearly always extends to the ground.

Defect will generally run 1-2 logs past exterior sign in old growth and 4-8' in second growth.

SIMPLIFIED RULES FOR DEDUCTIONS

Douglas Fir Western Larch Ponderosa Pine Lodgepole Pine White Pine (old growth) Grand Fir (2nd growth on W. Pine Site I & II) Spruce	Fungi - E. tinctorium - Fomes Pini - Deduct 1 log for 1 conk. (Cull each log that has 1 or more conks on it.) Figure rot extends 4' up and 6' down from conk, punk knot, or swollen knot.
Grand Fir (old growth & 2nd growth on all sites except W. Pine Site I & II) Alpine Fir Western Hemlock	Fungus - Echinodontium tinctorium Rot extends 1 log below first visible conk and 1 log above last visible conk.
Douglas Fir All Pines E. Spruce Larch	Fungus - Polyporuous Schweinitzil, velvet top fungus, causes butt rot. Deduct from 2'-8' (rarely more) depending on fungus development. 4' or 6% of tree volume will take care of most losses in 2nd growth, and 12% in old growth trees infected.
Western Larch	Defect - Massed pitch & shake. Mature and over-mature has this common defect and is evidenced by heavy butt swell and very thick ridges in bark of butt log. Defect generally sounds out where thick ridges in bark, and butt swell, stop.
White Pine (second growth)	Rot generally progresses from butt upward. Figure rot extends 2' up from highest conk and deduct portion of stem below this point. If only 1 conk is visible up on the stem, deduct 8' or 12% of tree's volume.

Log position in tree	Percentage distribution of gross merchantable volume (Scribner Decimal C) by logs, for trees* of indicated number of 16-foot logs per tree							
	2	3	4	5	6	7	8	9
	%	%	%	%	%	%	%	%
Butt	58	45	37	32	27	25	24	24
2	42	33	29	26	24	22	20	19
3		22	21	20	19	18	17	17
4			13	15	15	14	14	13
5				7	9	10	11	11
6					6	7	7	6
7						4	5	5
8							2	3
9								2
Tree total	100	100	100	100	100	100	100	100

* Includes following species: western white pine, ponderosa pine, white fir, Engelmann spruce, hemlock and larch.

Hamilton, David A., Jr., and Bruce M. Edwards
1976. Modeling the probability of individual tree mortality. USDA For. Serv. Res. Pap. INT-185, 22 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

This paper describes procedures for developing and testing models that predict the probability of individual tree mortality. The modeling procedures include data screening, parameter estimation, and model verification techniques that have been designed to deal with dichotomous dependent variables. To demonstrate the procedures, mortality models for 10 north Idaho species are developed and verified.

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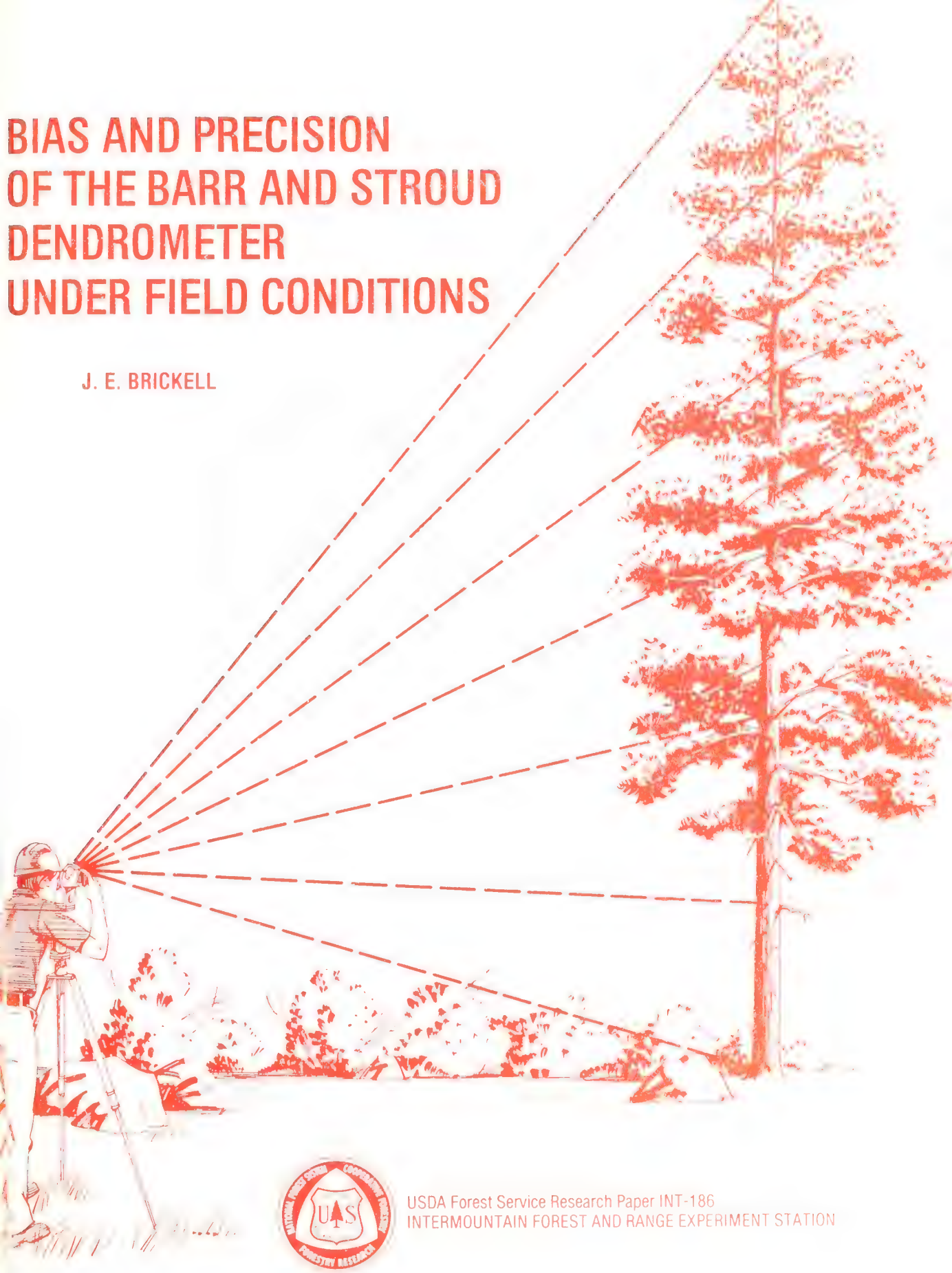
BIAS AND PRECISION OF THE BARR AND STROUD DENDROMETER UNDER FIELD CONDITIONS

J. E. BRICKELL



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1976

BIAS AND PRECISION OF THE BARR AND STROUD DENDROMETER UNDER FIELD CONDITIONS

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ABSTRACT

Field tests of the Barr and Stroud optical dendrometer disclosed a 1.19 percent bias in tree diameter measurements for each of three observers. No bias in height measurement was discovered. A 5.4 percent bias in standing tree volume measurement was attributed partly to diameter measurement bias and partly to wide spacing of measurement points on tree stems. Advantages and disadvantages of the Barr and Stroud dendrometer compared to other means of tree measurement are discussed.

Use of trade or firm names is for reader information only, and does not constitute endorsement by the U.S. Department of Agriculture of any commercial product or service.

INTRODUCTION

One of the problems encountered in the beginning of scientific forest management is still with us, the problem of estimating with accuracy and precision[1] standing timber volumes. This estimation process can be divided into two parts (Cunia 1965):

1. Obtaining an adequate and representative sample of trees from the population for which the volume estimate is sought, and

2. Measuring the volume of sample trees accurately and precisely.

The sample may consist of one tree or a small number of trees, or it may consist of a complete enumeration. Regardless of sampling design, no sample will yield a satisfactory estimate of timber volume unless volumes of individual trees can be obtained within the desired limits of accuracy. This estimate can be obtained directly or indirectly.

Direct volume measurement is an attempt to derive the actual volume of a sample tree from a series of measurements taken on that tree, usually by using a simple geometric solid as a model for segments of the tree stem. Tree volumes computed from a series of stem measurements on standing trees are direct measurements. Direct measurement also includes measuring the volume of water displaced when the tree stem is immersed in a tank.

Indirect volume measurement also uses tree measurements with some predicting device such as a volume table that predicts the average volume of trees having the same dimensions, usually only d.b.h. and height. Volume tables, which include predicting equations and alinement charts, have been the most commonly used means of tree volume estimation since 1780.

---

[1] In statistical terminology, accuracy means lack of bias, or the degree to which sample estimates represent the population parameters being estimated. Precision refers to the dispersion of estimates from repeated samples of the same size around their own average. The two terms do not mean the same thing.

Volume tables have also been misused. Proper use of volume tables usually requires that they be checked against a sample of trees measured by direct methods and adjusted if necessary. Most volume tables are not based on a sample drawn from the populations to which the tables will be applied. There may be no reason to suppose that the populations are greatly different, but biased volume estimates might be obtained if the assumption of no difference is not tested. Construction of a local volume table requires direct measurements of tree volume unless it is based on a standard volume table known to be applicable. If a tarif table system is employed, direct measurements of tree volume may be necessary to choose the correct tarif (Turnbull and Hoyer 1965).

Volume tables usually predict volumes only for undeformed, single-stemmed trees; so estimates may be reliable for well-managed stands where there are few abnormal trees. Where injured and forked trees are frequently found in unmanaged forests, the total volume estimate might be biased through procedures used to adjust tabular volumes for abnormal trees. Grosenbaugh (1964a, 1964b, 1965, 1967a, 1967b) devised the 3-P sampling technique, which can circumvent the use of volume tables and rely upon a sample of direct tree volume measurements as a sample of volume on a forest area. Properly used, the sampling method results in much less bias than could be expected from use of many volume tables.

Direct measurements of tree volume are usually obtained by measuring felled trees. Many foresters are reluctant to fell trees that may not be utilized, especially valuable species or crop trees under rotation age (Winters 1930). In addition to the loss of volume and growing stock, leaving felled trees provides breeding places for certain insects and increases fire hazard in the forest. Also, trees measured may not be the property of the party or agency conducting the survey. In other cases, such trees might be located on permanent sample plots that cannot be destroyed.

Climbing trees to obtain direct measurements also has certain disadvantages. Spurs injure cambium and provide infection courts for disease entry. Ladders long enough to be of use are too unwieldy and heavy to carry through a forest. Non-injurious climbing devices require a bole free of branches, yet the branches that prohibit their use generally are too small to support a man's weight. If branches are strong enough for climbing, hard shoe soles can injure them. These difficulties make tree climbing expensive and potentially unsafe.

Naturally, foresters have for many years wanted an instrument that would provide diameter measurements on standing trees with satisfactory accuracy. The Barr and Stroud dendrometer, manufactured by Barr and Stroud Ltd. of Glasgow, Scotland, appears to be the best optical instrument currently available for this purpose. It is also the most expensive.

The study reported here was to evaluate the Barr and Stroud dendrometer's accuracy and precision in a test situation and under actual field conditions. Dendrometer measurements taken under test conditions are compared with mechanical caliper measurements. Tree volumes computed from dendrometer measurements in the field are compared with volumes computed after the trees were felled. Dendrometer measurements of diameter at breast height and total tree height are compared with measurements taken with a tape. Finally, the utility of the Barr and Stroud dendrometer for various tree measurement objectives is compared with the utility of felled-tree measurements and those taken with other optical instruments.

LITERATURE REVIEW

Early Dendrometers

Dendrometers to measure standing trees have existed for nearly 200 years (Fernow 1907; Prodan 1965). At least eight different dendrometers were available in Europe at the beginning of this century (Clark 1902; Graves 1906).

Between 1920 and 1950, dendrometer inventions appeared periodically in the literature (Lönroth 1926; Schumacker 1926; Winters 1930; Hartman 1949). Bitterlich's relaskop was a development of the 1950's and 1960's (Bitterlich 1952, 1958, 1962; Daniel and Sutter 1955; Sutter 1965). McClure (1969) independently invented a mirror caliper similar to that of Heikkila (1932). For a more complete review of previous concepts and instruments see the papers of Hummel (1951) and Grosenbaugh (1963).

Optical Rangefinder Dendrometers

Dendrometers Similar to the Zeiss Teletop

Apparently, the Zeiss Teletop (Ruden 1939; Prodan 1965; Mesavage 1969b) was the first optical rangefinder dendrometer with an optical rangefinder of variable base length. An unmodified Teletop is shown in figure 1. Fricke (1967) modified the

Figure 1.--The unmodified Zeiss Teletop.

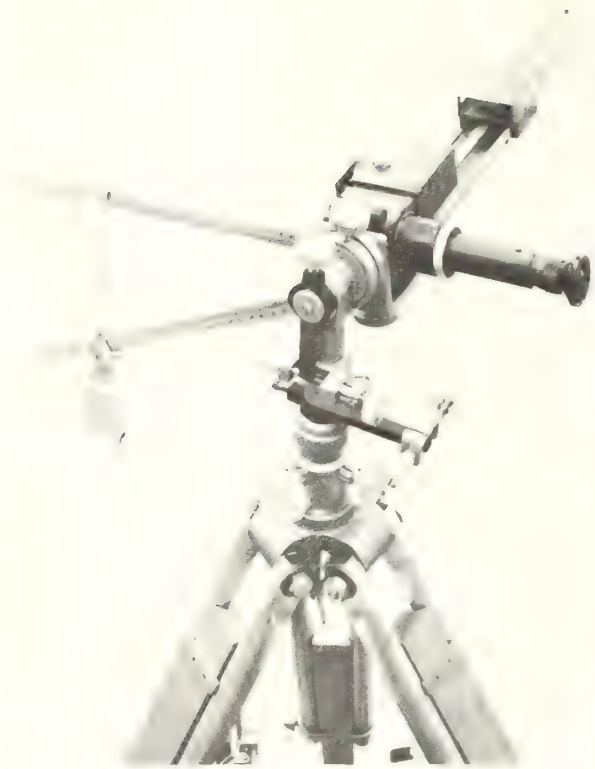


Figure 2.--Fricke's Universal Teledendrometer (UTD).

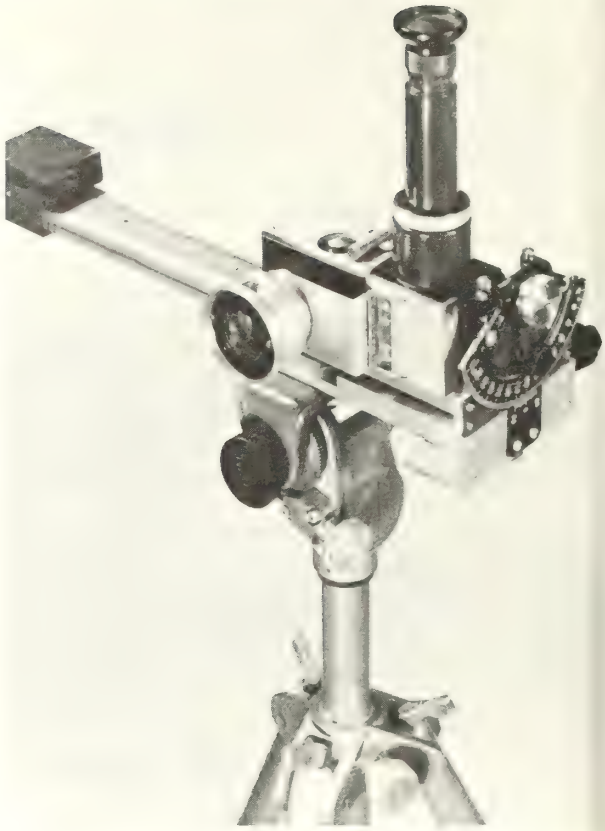


Figure 3.--Mesavage's modified Teletop dendrometer.

Teletop to develop the Universal Teledendrometer (UTD) (fig. 2). Mesavage's modified Teletop dendrometer (Mesavage 1969b) (fig. 3) incorporated improvements over both the unmodified Teletop dendrometer and Fricke's UTD.

Recently, the Todis dendrometer, manufactured in Germany by F. W. Breithaupt & Sohn, has been offered for sale in the United States. The Todis also uses a variable length rangefinder.

The Barr and Stroud Dendrometer

In 1947, Hummel and Laurie of the British Forestry Commission saw the possibility of using an optical rangefinder to measure tree diameters. Barr and Stroud Ltd. of Glasgow, Scotland, undertook development of a dendrometer based on a rangefinder originally used for tank gunnery. Hummel's (1951) paper mentioned trial of an early model of the Barr and Stroud dendrometer. In 1953 the Barr and Stroud dendrometer, type F.P. 7, was produced. It gave 5.5 image magnification, had a rangefinder base length of 8 inches, and an inclinometer graduated in sine of elevation angle. These features have been common to all subsequent models of the Barr and Stroud dendrometer. A major fault in the design of the F.P. 7 was the inability of the inclinometer to record an angle of depression.

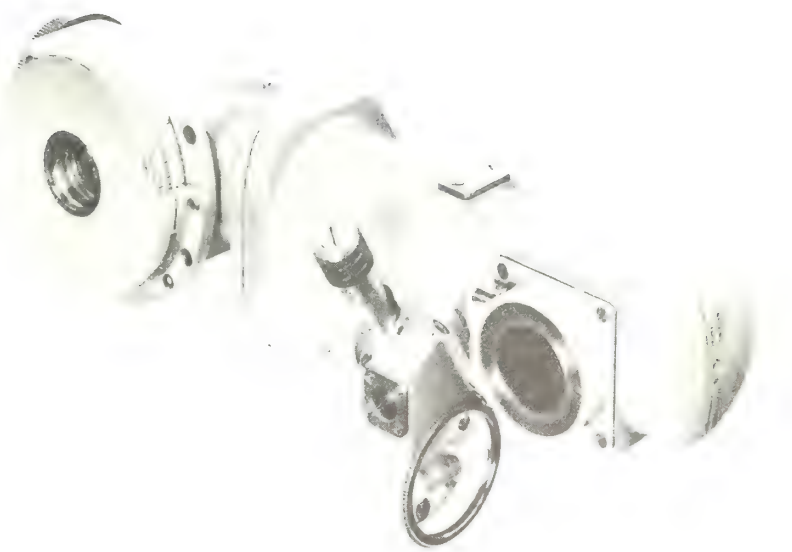


Figure 4.--The Barr and Stroud dendrometer, Model F.P. 9.

The F.P. 9 Barr and Stroud dendrometer (fig. 4) was the first model commercially available in the United States (Mesavage 1967). The F.P. 9 could measure angles of depression up up to 25 degrees. The Barr and Stroud Model F.P. 12 dendrometer (fig. 5) improved on the F.P. 9 chiefly by being easier to use rather than giving more accurate measurement. The F.P. 15, most recent model of the Barr and Stroud dendrometer, incorporates refinements recommended by Hartman (1967) and Mesavage (1967). These include a translucent lens barrel for the scale-reading eyepiece to admit adequate

Figure 5.--The Barr and Stroud dendrometer, Model F.P. 12.

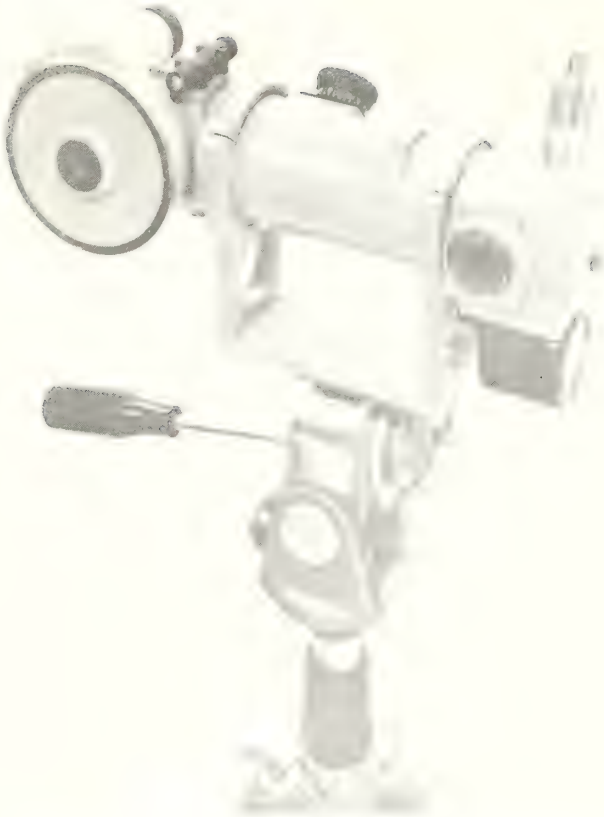


Figure 6.--The Barr and Stroud dendrometer, Model F.P. 15.

light in dense shade, and limits of 60 degrees for both elevation and depression angle. As shown in figure 6, a sight was added to the F.P. 15 for rapid aiming at the tree stem. Also, the inclinometer is graduated in terms of (1 + sin) to prevent confusion between negative and positive readings in the neighborhood of zero elevation (Mesavage 1969a).

The successive modifications that have led to a series of models of the Barr and Stroud dendrometer have not been basic changes of design; consequently, the latest instrument cannot be expected to be more accurate than its predecessors.

Various trials and use of the Barr and Stroud dendrometer have been reported by Jeffers (1956), Grosenbaugh (1963), Bouchon (1967), Bruce (1967b), Hartman (1967), Van Schie (1967), Arvanitis (1968), Bell and Groman (1968, 1971), Bower (1971), Langley and others (1971), Wensel (1971), and Wensel and Schoenheide (1971).

Presently existing literature on the use of the Barr and Stroud dendrometer shows a diversity of findings ranging from a serious deficiency in accuracy (Bouchon 1967) to excellent accuracy (Bell and Groman 1968, 1971). Some workers have obtained a satisfactory level of accuracy only by using the dendrometer in association with other instruments and increasing complexity of the measurement process to the point where efficiency of fieldwork is greatly reduced (Van Schie 1967). Others, while conceding the superior accuracy of the Barr and Stroud, consider its advantages over certain other instruments doubtful for practical work because of initial instrument cost and the rapidity with which measurements are made (Pfeiffer 1967; Arvanitis 1968).

In almost all cases cited in the literature where diameter measurements taken with the dendrometer differed from those taken with mechanical calipers, the dendrometer measurements were somewhat larger. This was the case even when the difference was of no statistical nor practical significance.

A TEST TO EVALUATE BIAS OF DENDROMETER DIAMETER MEASUREMENTS

To obtain a check on dendrometer measurements of diameter as precise as any that could be made under field conditions, an experiment was conducted in which three observers took dendrometer measurements and compared them with caliper measurements taken at the same point on each tree stem. The observers will be designated in this report by their respective initial, P, B, or R.

Nature of the Sample

Open stands of ponderosa pine (*Pinus ponderosa* Laws.) on level or nearly level terrain were chosen for the experiment to minimize extraneous difficulties. So little underbrush was present that it presented no obstacle to the use of the instrument. The experiment was conducted in clear weather and light conditions were excellent due to the open character of the stands. Several instrument locations were established in each of three stands. Sample trees were selected by systematically measuring d.b.h. of all normally formed trees visible within reasonable distance of the instrument location.

Measurements were taken of 88 trees, but one was subsequently rejected because of a dendrometry mistake. The trees ranged from 5.2 to 31.2 inches d.b.h. (caliper measurement) and were of normal form at the point of measurement.

Methods

A pair of wooden calipers, large enough to measure trees up to 36 inches in diameter, was carefully adjusted before being used in the experiment. Calipers were checked again after all tree measurements were taken and were still in proper adjustment. The dendrometer tested was an unmodified Barr and Stroud instrument, Model F.P. 12. Halving and coincidence adjustments were checked before and after measurement according to the manufacturer's instructions.

Each sample tree was marked at breast height before measurement. A strip of plastic flagging was carefully wrapped around the tree and tied so that the knot would not interfere with use of the calipers.

Care was taken with every tree to see that the diameter measured with the calipers was perpendicular to the line of sight from the instrument location to the tree and was, as nearly as possible, the diameter that would be measured with the dendrometer. Caliper measurements were agreed upon by all three observers.

After the caliper measurement of diameter was recorded, each observer took a set of dendrometer readings. After taking measurements, each observer disturbed the instrument setting so that the next man could establish his own coincidence settings. To assure independent measurements, no observer had prior knowledge of what instrument readings should be. This measurement routine was followed for each tree in the sample.

Compilation of Data

Tree diameters were computed from the corresponding dendrometer readings with the computer program NETVSL (Stage and others 1968), which uses formulas published by Grosenbaugh (1963) for his computer program, STX (Grosenbaugh 1964b, 1967b). NETVSL uses double precision arithmetic in evaluating the formulas. To perform such computation, a set of instrument constants is necessary. These constants serve as coefficients in the formulas. When the data for this study were compiled, three sets of instrument constants were available:

1. Those derived empirically and published by Grosenbaugh (1963) that assume a glass-refractive index of 1.523 and a mean prism-deflection angle for the instrument of 135.0 minutes;

2. Those derived later from the manufacturer's design parameters and published by Grosenbaugh (1967b) that use the glass-refractive index given by Barr and Stroud Ltd.; and

3. A set of constants computed by Grosenbaugh's (1963) exact method, using the exact glass-refractive index 1.5658 and a mean prism deflection angle (MPD) of 136.29 minutes. This MPD was obtained from direct calibration of the instrument used in this study.

The values of the constants in these three sets are shown in table 1. The instrument constants labeled B, Q, U, and G refer to characteristics of the instrument's design and manufacture. These constants are necessary to convert dendrometer readings to diameters and distances.

The data collected for this study were compiled three times, using the three sets of instrument constants; so diameters computed with each set of constants could be compared with the calipered diameters. Each of the three observers had three sets of 87 dendrometer diameters to compare with the caliper measurements. Caliper measurements were considered to be correct for the purpose of evaluating bias and error of dendrometry. So nine sets of 87 diameters were tested against the caliper measurements. Analysis of the data is described in appendix A.

Table 1.--*Values of the instrument constants in the three sets used for data compilation in comparing dendrometer diameters with calipered diameters*

Set of constants	Labeled instrument constants[1]			
	B	Q	U	G
Grosenbaugh's old constants (GO)	8.0	0.01970203	-1.1933	1.523
Grosenbaugh's new constants (GN)	8.0	.01964673	-1.1905	1.5658
Direct calibration constants (DC)	8.0	.01982151	-1.2012	1.5658

[1]These constants, which refer to characteristics of the instrument's design and manufacture, are necessary to convert dendrometer readings to diameters and distances.

Discussion and Conclusions

The choice of instrument constants for the compilation of dendrometer data may not be critical, providing that the constants do not differ from the optimum set by more than the constants in this experiment differed from each other. In this experiment, three sets of instrument constants were used and, at one time or another, each seemed to provide satisfactory results. No significant differences were detected between the estimates obtained with each of the sets. Likewise, no significant difference was detected between the measurements made by three different observers.

Whatever its source, a positive bias of about 1.19 percent was found when dendrometer estimates of tree diameter were compared to caliper estimates of the same diameters. This bias would amount to about 2.39 percent bias in estimating a cross-sectional area of the stem. Grosenbaugh (1963) reported a basal area overestimate of about 0.7 percent in a similar trial involving fewer trees. Also, bias seemed to increase with the size of tree, hence its expression as a percentage above. The absence of a regression intercept different from zero indicates no constant component of bias that would remain the same for all trees.

The "pure" error remaining after bias is removed is also correlated with the diameter of the tree being measured. This was the reason for weighting the observations in regression calculations. An unqualified statement of error cannot be made. However, two-thirds of the time, the error discovered in this experiment was less than 0.03 inch for 5-inch trees and less than 0.2 inch for 30-inch trees. These results suggest that after any needed removal of bias, dendrometer diameter measurements taken by an observer working under good stand and weather conditions will be within a quarter of an inch of calipered measurements at least two-thirds of the time. This assumes the range of tree sizes usually encountered in the Mountain States.

Source of Bias

The source of the bias demonstrated by this experiment is not readily apparent. Possibly none of the instrument constants used were quite applicable. Certainly, they could be adjusted, perhaps to some least squares criterion of agreement between dendrometer and calipers as Grosenbaugh (1963) suggested. However, the fact that the three

sets of instrument constants shown in table 1 gave essentially the same results suggests that fairly severe adjustment might be necessary to obtain unbiased measurements. It is questionable whether such methods would be justified to adjust parameters that have been derived exactly from known standards of manufacture. Apparently, no dissatisfaction with the two previously published sets of constants has been registered by those who have used the Barr and Stroud dendrometer. The possibility of adjusting the instrument constants in no way establishes them as the source of bias discovered in this experiment.

Another possible source of bias is the difference between the tree diameter measured with the calipers and the two radii estimated with the dendrometer. It is assumed that the angle measured with the dendrometer exactly subtends a circle (the tree cross section) with two radii perpendicular to the points at which the sides of the angle are tangent to the circle.

Most tree cross sections are more nearly oval than circular (Müller 1957; Chacko 1961); nevertheless, when a diameter is assigned to a tree stem, a circular shape is necessarily implied. If one number must be used to describe this "diameter," then it is best if the number, D, is such that $\pi/4\ D^2$ gives the cross-sectional area of the tree even though it is not circular. If the cross section is elliptical, such a diameter can be computed by

$$D = 2\sqrt{ab}\ ,$$

where a and b are the semimajor and semiminor axes of the ellipse (Goosens 1967). This pseudodiameter adequately serves the purposes of tree volume calculation because it gives the true area of the appropriate ellipse when used in the formula for area of a circle. Apparently, dendrometer diameter estimates of noncircular stems are biased. However, Grosenbaugh (1963) stated that the magnitude of the bias is only slightly more serious than similar biases that foresters have long tolerated with mechanical forks, calipers, or tapes. For elliptical trees having the short diameter nine-tenths of the long diameter, an overestimate in cross-sectional area of about 0.4 percent will be obtained with a diameter tape (Chaturvedi [1926]; the Imperial Forestry Institute [1944]). Apparently, the bias in dendrometer measurements caused by noncircular stems is not much larger than that.

However, this explanation of the bias discovered by this experiment is not supported by the nature of the bias indicated by the regression equation. The baseline of the dendrometer's rangefinder is 8.0 inches; so when the diameter of the subject tree is 8.0 inches, no angle exists. The lines of sight from the dendrometer are parallel; so the instrument becomes, in effect, an optical caliper. Only when measuring trees of this size are the two radii measured with the dendrometer coincident with tree diameter perpendicular to the line from the center of the tree to the instrument location--the diameter measured with calipers in this experiment. For this reason, the expected apparent bias would be zero for trees 8.0 inches d.b.h. One would then expect a negative intercept in the regression of dendrometer diameter on calipered diameter so that the regression would pass through the point (D_c = 8.0, D_d = 8.0) and the weighted grand mean. Therefore, an underestimate of diameters by the dendrometer would be implied for trees smaller than 8.0 inches d.b.h. The fact that trees approximately 8.0 inches by caliper measurement also receive an overestimate casts doubt on this explanation of any substantial component of bias.

Rounding or truncation error in the calculation of diameters from dendrometer readings might attach a bias to the resulting diameters. However, calculations for this experiment were done with double precision arithmetic on an IBM 360 computer (Stage and others 1968). At least 15 significant digits were guaranteed in computation; so it is unlikely that rounding error could have any noticeable effect on computed diameters. Although they were not used for comparisons, dendrometer diam-

eters were also read from tables furnished by Barr and Stroud Ltd. Tabular diameters are less accurate than those computed with the formulas but, nevertheless, they showed a tendency for dendrometer diameters to exceed those taken with mechanical calipers.

Such overestimates could also result from inaccuracies inherent in human vision. Stage (1962) conducted experiments on the displacement of a tree stem image by the wedge prism which showed the presence of personal bias. Joseph P. McClure (personal communication) described an experiment in which observers were asked to move a prism back and forth along a line of sight until they judged from image displacement that the distance to a particular tree made it a marginal tree. Measurement of the distance with a tape usually showed that the distance was actually greater than the limiting distance computed from the tree's diameter. Ross (1968) took diameter measurements on some test trees with a Wheeler penta prism caliper in two ways, and found a statistically significant difference between diameters measured by the two methods. The instrument and the principles of its operation are exactly the same in both cases; so I attribute the difference between average measurements to some human characteristic.

Jeffers (1956) reported that some observers slightly overestimated tree diameters with the Barr and Stroud Model F.P. 7 dendrometer. Van Schie (1967) reported similar overestimates with a later model, as did persons using dendrometers based on the Zeiss Teletop (Fricke 1967; Bower 1971).

Such bias might be caused by poor definition of a tree's edge resulting from rough bark, but use of plastic flagging to provide a clearly defined edge did not eliminate the bias. In some cases, mechanical calipers could compress the bark, thereby providing check measurements somewhat smaller than those taken with the dendrometer. But, on trees with tight, hard bark, considerable pressure would be required to close steel calipers to 0.1 inch less than the correct measurement. Bark probably could not be compressed without bending wooden calipers.

It may well be that the bias in dendrometer measurements shown by this experiment arises from several sources. The information obtained from this experiment permits no definitive statement about dendrometer bias beyond the fact that it does exist, is of given magnitude, and is essentially the same for three different observers.

DENDROMETER MEASUREMENTS OF DIAMETER, HEIGHT, AND VOLUME UNDER AVERAGE FIELD CONDITIONS

The Study Area

Average field conditions in northwestern Montana are not the most pleasant for fieldwork. Steep hills, a dense understory in many places, and much fallen timber result in challenging conditions for testing the accuracy of an instrument. Some trees, especially Engelmann spruce (*Picea engelmannii* Parry) and the firs (*Abies* spp.), have dense crowns that severely limit visibility of upper stems. Yet, these are average field conditions for the area, and it was under such conditions that the trial described was carried out. Tests conducted in an open stand of pines might minimize observer error, but they would hardly test the feasibility of the instrument's use under average conditions, unless open pine stands constitute the average condition.

Procedures

Sample Tree Selection

Field tests of the Barr and Stroud dendrometer were part of a study designed to test net volume sampling methods. Methods involved felling some trees at each location to estimate cull volume and measuring others with the dendrometer to estimate gross volume. By first measuring some trees to be felled with the dendrometer, we were able to examine the precision and accuracy of dendrometer measurements, and to decide what adjustment, if any, might be required.

At that time, the sampling unit for forest inventories used by the Forest Service's Northern Region was a cluster of 10 variable radius plot sampling points, often referred to as a "location." Each sampling point within the cluster was 70 feet from the nearest adjacent point. Trees were selected for measurement from each point with a critical angle corresponding to a basal area factor of 40. From the trees tallied for basal area estimation on each of 39 locations, a subsample was selected to be felled and measured for purposes of cull volume estimation. Another subsample was selected for measurement with the dendrometer to provide a gross volume estimate of the trees that were not felled. It was further specified that of the trees to be felled on each location, those with the largest and smallest diameter at breast height would be measured with the dendrometer. This was a means of checking dendrometer measurements. Trees of abnormal form or having defective boles were not purposely excluded. Thus, a sample was obtained of 78 trees, which were measured with the dendrometer while standing and after felling. Diameter breast height ranged from 5.1 to 43.1 inches.

Dendrometer Measurement Procedures

Dendrometer measurements were taken in the following manner. Stump diameter outside bark was measured with a diameter tape at a point 1 foot above the ground. Then, a strip of plastic flagging was wrapped around the trunk at breast height (4.5 feet) and d.b.h. was measured with a diameter tape. Two measurements of bark thickness at breast height were taken at right angles to each other with a Swedish bark punch. The sum of these two bark thickness measurements was the estimate of double bark thickness at breast height.

The dendrometer then was set up at a suitable instrument location. Diameter at breast height was measured with the dendrometer. Flagging not only marked breast height but provided a clearly defined target for taking true and false coincidence readings. Measurements at other heights on the stem were then taken at certain points above breast height. Because the tree crown sometimes hides portions of the bole, it is not practical to prescribe fixed heights at which dendrometer measurements will be taken. However, wherever possible, measurements were taken at no fewer than eight levels on the tree stem and at the top of the tree to accurately establish total height. Most trees had five measurements taken between breast height and the tree's top. Dendrometer measurements were recorded on a field form designed by Floyd Johnson of the Pacific Northwest Forest and Range Experiment Station (fig. 7).

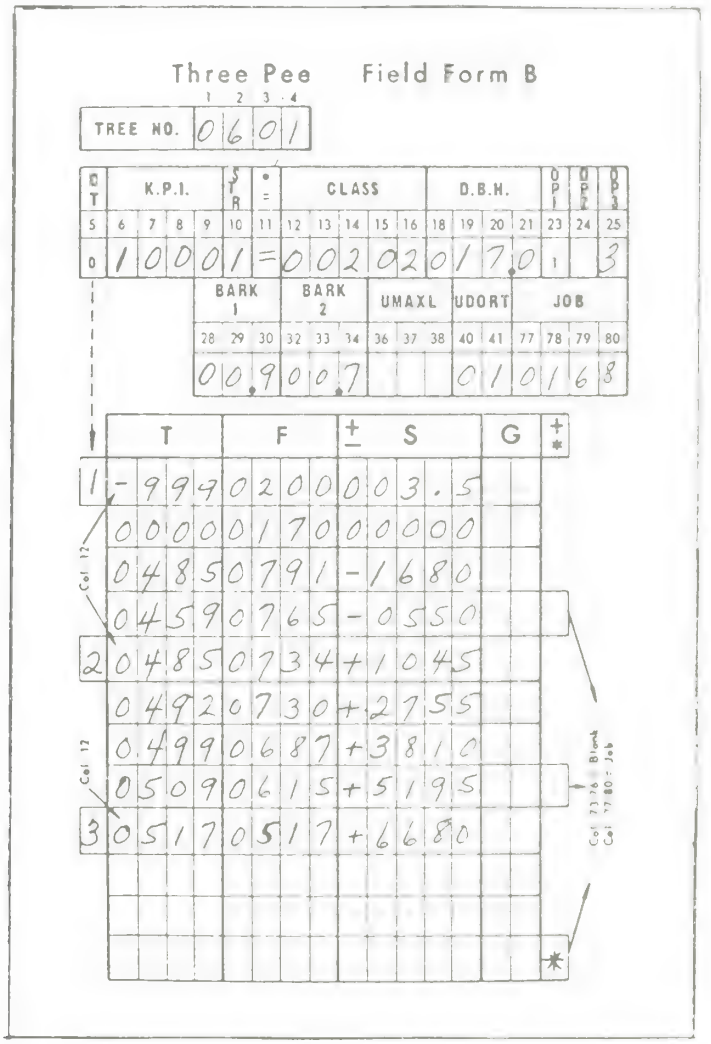


Figure 7.--The form used to record dendrometer measurements in the field.

Measurement of Felled Trees

Diameter and bark thickness measurements on felled trees were taken at stump height (1.0 foot), breast height (4.5 feet), and at alternating 8.1- or 8.2-foot intervals on the stem. This spacing was used to obtain measurements at intervals of 16.3 feet because National Forest personnel who assisted in the collection of data wished to apply their log scaling rules to felled trees. In some cases, the stem was cut and measured at 4-foot intervals to determine the location of cull volume. Diameter measurements were taken across the cut section of the stem on two axes that best represented the cross-sectional area of the stem. In the absence of deformities or abnormalities on the stem, these were the long and short axes of the cross section. Both diameter inside bark and diameter outside bark were measured by stretching a steel tape across the cut section of the tree trunk. The cross-sectional area of felled tree stems was computed as though the cross section were elliptical in shape. That is,

$$A = \pi ab$$

where

A = cross-sectional stem area (either inside or outside bark, depending upon whether or not a and b include bark)

a = the semimajor axis of the assumed ellipse

b = the semiminor axis of the ellipse

The cross section of a tree stem can more generally be described as an oval, not necessarily elliptical or circular. Matérn (1956) generated six such ovals (including an ellipse) by functions in polar coordinates. Their exact area was calculated and compared with area estimates obtained from 10 different methods of tree diameter measurement. For five of the six ovals, the diameter obtained from the geometric mean of measurements on the maximum and minimum axes gave the smallest bias in estimation of area. The diameter used in this study to describe the tree trunk at various points was:

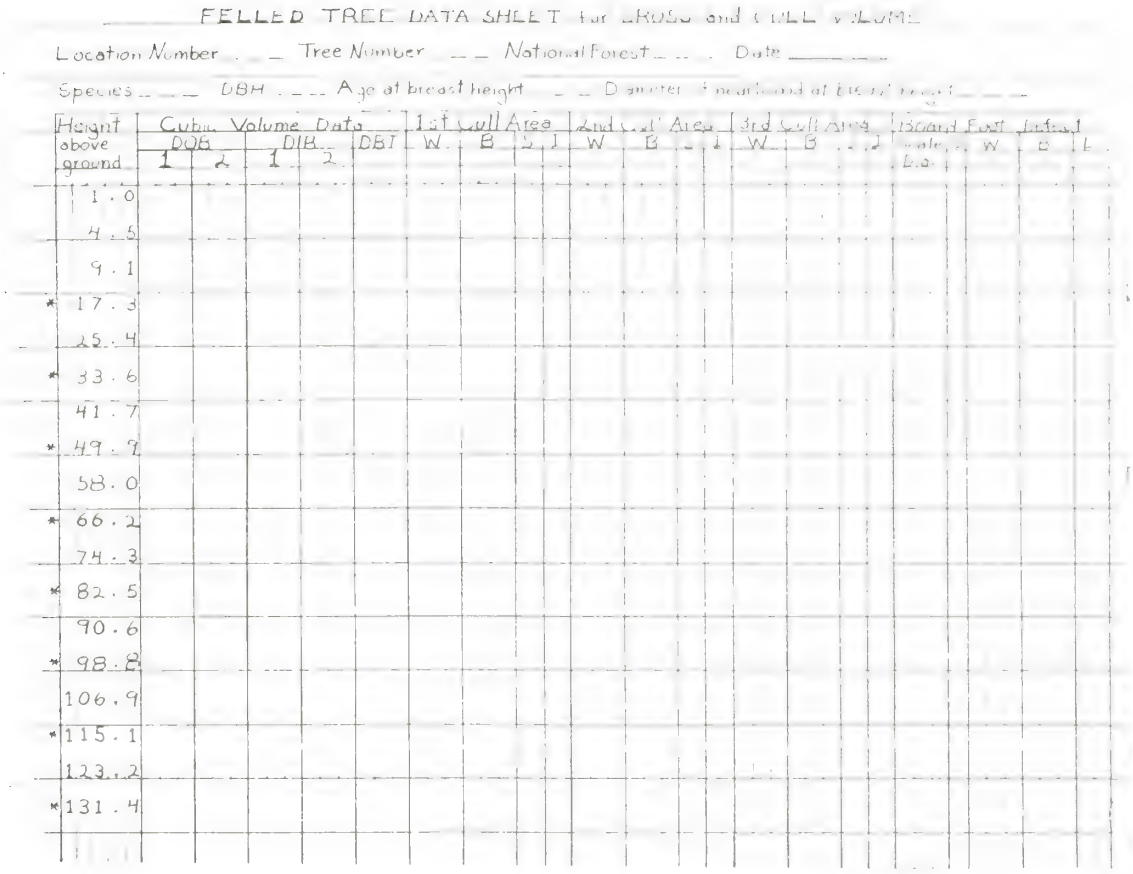
$$D_f = 2\sqrt{ab}$$

When used in the formula for area of a circle, this diameter gives the tree's cross-sectional area as nearly as is practical with no more than two measurements. Only measurements on the long and short axes of the cross section were recorded in the field. Area and the corresponding pseudodiameter were computed during data compilation. Data were recorded on a specially prepared form (fig. 8). Felled tree measurements were recorded in feet and in tenths and hundredths of feet.

Tree Volume Computation

A computer program was used to obtain volumes for both felled trees and those measured with the dendrometer. For a description of the program and its use, the reader is referred to Stage and others (1968). The computer program NETVSL (net volume, surface, and length) can be used to compute gross, cull, and net volumes, as well as surface area of trees from measurements of stem length and diameter. Measurements on standing trees cannot be used to compute cull volume.

By proper selection of its built-in options, the program can be used to compute total cubic volume in the tree, cubic volume between a specified stump height and a specified top diameter, and board-foot volume between a specified stump height and top diameter. Board-foot volume can be computed according to the Scribner rule, the International 1/4-inch rule, or both. Various combinations of differently specified


FELLED TREE DATA SHEET for CROSS and CUBIC VOLUME

Location Number ___ Tree Number ___ National Forest ___ Date ___

Species ___ DBH ___ Age at breast height ___ Diameter (mean) and at breast height ___

Height above ground	Cubic Volume Data DOB 1	DOB 2	DIB 1	DIB 2	DBT	1st Cull Area W	1st Cull Area B	1st Cull Area L	2nd Cull Area W	2nd Cull Area B	2nd Cull Area L	3rd Cull Area W	3rd Cull Area B	3rd Cull Area L	Board Foot Scale Log	Board Foot Interval W	Board Foot Interval B	Board Foot Interval L
1.0																		
4.5																		
9.1																		
* 17.3																		
25.4																		
* 33.6																		
41.7																		
* 49.9																		
58.0																		
* 66.2																		
74.3																		
* 82.5																		
90.6																		
* 98.8																		
106.9																		
* 115.1																		
123.2																		
* 131.4																		

Figure 8.--The form used to record felled-tree measurements in the field.

volumes can be computed in one execution of the program. For this study, all comparisons of tree volume estimates were based upon cubic volume of the total stem, including bark. Inaccurate estimates of bark thickness can bias the estimate of tree volume inside bark, yet this bias has nothing to do with dendrometer accuracy.

For computation of total tree volume, the volume below the first diameter measurement is computed as though the stump were a cylinder of the given length and diameter. The volume of the section terminating at the tip of the tree is computed as though the section were a right cone. Intervening sections of normal taper are treated as right parabolic frustrums, and their volume in cubic feet is computed by Smalian's formula. If the diameter at the top of a stem section is larger than the next lower diameter, indicating negative taper, the intervening section is treated as an inverted right conic frustrum. This geometric model has serious shortcomings, especially for calculating volume in the lower portion of a tree. Further, if these deficiencies are ignored, the results of this study could be misinterpreted.

Dendrometer D.B.H. Versus Taped D.B.H. Under Average Field Conditions

On each of 403 trees measured with the dendrometer (including the 78 trees subsequently felled), two measurements were taken of d.b.h.--one with the dendrometer and one with a steel diameter tape. Breast height was marked by a piece of plastic flagging, measured with a tape, and recorded. Then, the dendrometer was set up at a suitable location and d.b.h. was measured and recorded again. The linear regression of

d.b.h., measured with the dendrometer on taped d.b.h., was fitted to the sample of paired observations. To attain homogeneity of variance around the regression line, it was necessary to assign each pair of observations a weight inversely proportional to the square of the taped measurement. Weights were scaled so that the sum of weights was equal to the number of observations. The fitted regression was:

$$\hat{DBH}_d = \hat{b}_0 + \hat{b}_1 \, DBH_t$$

where

b_0 = 0.10712

b_1 = 0.996676

S_a = standard error of b_0 = 0.0492664

S_b = standard error of b_1 = 0.0050488

r^2 = coefficient of determination = 0.989815

For testing the differences of $\hat{b}_0$ and $\hat{b}_1$ from zero and unity, respectively, the t statistics are:

$$t_{b_0} = \hat{b}_0/S_a = 2.1745$$

$$t_{b_1} = (1 - \hat{b}_1)/S_b = 0.658275$$

The hypothesis that the regression intercept is not different from zero is rejected, but the hypothesis that the slope of the regression line is not different from unity is retained. If $b_1 = 1.0$, then the estimate of the regression intercept is the difference between means of the variables. The weighted means are:

$$\overline{DBH}_t = 8.8289899 \text{ inches}$$

$$\overline{DBH}_d = 8.9017811 \text{ inches}$$

giving an estimated regression intercept of 0.07779 inch. This figure indicates a positive bias in dendrometer diameter estimates that is less than 0.1 inch and is not correlated with tree size. As a percentage of diameter, this bias would decrease from 1 percent for trees of 7.8 inches d.b.h. to about 0.25 percent for trees of 30 inches d.b.h. For most work, this bias is not large enough to cause concern.

When dendrometer measurements were compared with caliper measurements, positive bias was a constant percentage of diameter. The reason for correlation between diameter and bias in one case and not in another is not evident. Even on trees of irregular cross-section shape, Matérn (1956) has shown that the expected value of a single caliper measurement is the same as the measurement obtained with a diameter tape. The caliper measurement would carry a larger error, but the mean diameter of a sample of trees would be expected to be the same for both measurement methods; so the standard against which the dendrometer measurements of diameter were compared had the same expected value in both cases (Brickell 1970a).

Barr and Stroud give the "approximate uncertainty of observation" for diameters measured with the dendrometer as 0.1 inch for trees up to 10 inches in diameter and 1 percent for diameters larger than 10 inches. They do not explain why it is constant up to a particular size and proportional to diameter beyond that size.

The arithmetic mean diameter of the 87 calipered trees was 17.7 inches and the unweighted arithmetic mean of the 403 taped trees measured on inventory locations was

13.7 inches. In one sample, trees may tend toward sizes for which the uncertainty of observation is a constant 0.1 inch, whereas in the other sample, larger trees may tend toward a percentage uncertainty. Weights given the observations for regression in both samples would have given small trees more influence on the regression line than large trees. Of the 87 calipered trees, only seven trees, about 8 percent, were 10 inches or less in diameter; but 154, about 38 percent of the taped trees, were 10 inches or less in diameter. Unfortunately, this explanation of the nature of diameter estimation bias will not suffice if the term "uncertainty of observation" as used by Barr and Stroud means random error. Unless error and bias of dendrometer measurements are related, this study cannot explain the apparently different forms of diameter measurement bias in the two samples. However, regardless of the form of the bias, it is positive (an average overestimate) in both cases.

Plastic flagging wrapped about the tree at breast height was intended to allow more accurate setting of true and false coincidence. It may have increased accuracy and precision, but reduction of the uncertainty in coincidence settings due to a rough and indistinct bark edge did not remove all sources of bias. However, flagging is recommended in measuring trees with the dendrometer as it serves a practical purpose: the tree to be measured can be easily seen against a forest background. If adjacent trees are of the same species and size class, it is sometimes easy to become confused if some sort of marker is not used.

Bias and Precision in Height Estimation

Height measurements for 6 of the 78 trees measured with the dendrometer and subsequently felled were obviously mistakes. These were set aside. Remaining height measurements yielded the following statistics:

$\overline{H}_d$ = 78.118042 feet $\quad S_H$ = 27.692017 feet

$\overline{H}_f$ = 77.740265 feet $\quad S_{H_f}$ = 27.738711 feet

where

$\overline{H}_d$ = mean of dendrometer height measurements

$\overline{H}_f$ = mean of taped height measurements after felling

S_{H_d} = standard deviation of dendrometer measurements

S_{H_f} = standard deviation of taped measurements.

The mean difference ($\overline{H}_d - \overline{H}_f$) equals 0.377777 foot. The correlation coefficient of the two sets of measurements is 0.99821. So the standard deviation of differences between taped and dendrometered measurements is:

$$S_{(H_d - H_f)} = \sqrt{S^2_{H_d} + S^2_{H_f} - 2\,(0.99821\,S_{H_d}S_{H_f})}$$

$$= 1.6622 \text{ feet.}$$

The standard error of the mean difference obtained by division:

$$S_{\overline{(H_d - H_f)}} = \frac{S_{(H_d - H_f)}}{\sqrt{72}} = 0.19588 \text{ foot.}$$

To test the hypothesis that no constant bias exists in height measurements with the dendrometer, Student's t test was applied. The t statistic is obtained by division:

$$t = (H_d - H_f) \; / \; S_{\overline{(H_d - H_f)}}$$

$$= 1.9286.$$

Thus calculated, t is less than the value necessary to reject the hypothesis at the 95 percent confidence level; so the hypothesis of no bias was retained.

To illustrate further the absence of bias in dendrometer height measurements, the regression

$$\hat{H}_d = \hat{b}_0 + \hat{b}_1 H_f$$

was fitted to the paired measurements with the result:

$$\hat{b}_0 = 0.77003 \qquad S_{b_0} = 0.58722021$$

$$\hat{b}_1 = 0.99495429 \qquad S_{b_1} = 0.00711863.$$

The t statistics

$$t_0 = \hat{b}_0 / S_{b_0} = 1.3113138$$

$$t_1 = (1 - \hat{b}_1) \; / \; S_{b_1} = 0.708803$$

do not justify rejection of the hypothesis that the coefficients b_0 and b_1 equal zero and unity, respectively, and that, therefore, H_d equals H_f.

If $b_1 = 1$, then there is no correlation between tree height and measurement differences--between $(H_d - H_f)$ and H_f. Also, variance about the regression was not related to tree size.

This finding that the Barr and Stroud dendrometer provided an unbiased means of estimating tree heights differs from results of Bouchon's (1967) study. In that case, heights measured with the dendrometer were compared with heights of the same trees measured with a Wilde-TO theodolite. Sample trees ranged from 5 to 98 meters in height. An important negative bias was observed, the mean of which was -80.5 centimeters for 20 trees.

Bouchon found that this bias was caused by a consistent underestimate of the horizontal distance from the instrument location to the subject tree. Conventional practice uses slope distance from the instrument to the point of measurement with the sine of angle of elevation to compute tree height. When a chained distance was substituted for the one obtained from the dendrometer measurements, the bias virtually disappeared. Before such correction, the standard deviation of differences in height measurement was 58.4 centimeters (1.92 feet); after correction, it was 3.26 centimeters. Thus, while the standard deviations of the differences (measured height — actual height) do not seem to differ greatly between the present study and Bouchon's, the French experiment disclosed a bias in height (or distance) measurement not encountered in this study. The reason for Bouchon's underestimate of horizontal distance is not apparent.

Jeffers' (1956) trial of the Model F.P. 7 Barr and Stroud dendrometer disclosed no bias in estimates of distance or height. For differences between true measurements and dendrometer measurements taken by several observers on a number of trees, Jeffers

gives approximate standard deviations of 1 foot in range and one-half foot in height. It is assumed that these are standard deviations about the true measurements. Barr and Stroud (*Pamphlet 1217K*) give the approximate uncertainty of observation under average practical conditions as 1.5 percent for height.

In this study, the standard deviation of differences between dendrometer height and true height, expressed as a percentage of mean true height, is:

$$(S/\overline{H}_f) \times 100 = (1.6622/77.74) \times 100 = 2.14 \text{ percent.}$$

This exceeds the Barr and Stroud figure, but not by an important amount.

It may be worthwhile to compare test statistics obtained for the dendrometer in this study with the results of tests conducted on other height measuring instruments. Warren (1958) examined accuracy and precision of the Abney level, the Haga altimeter, and the Blume-Leiss altimeter (Parde 1955). Five observers measured the same 15 trees in each of three different stands. The trees were climbed and measured with a tape to provide standard heights with which the instrument measurements could be compared. Hunt (1959) used a transit to establish standard heights of a number of trees. Measurements were then taken with the Haga altimeter, the Engineers hypsometer (similar to the Forest Service hypsometer [Krauch 1918], but smaller), the Abney level, and the Spiegelrelaskop (Daniel and Sutter 1955; Bitterlich 1958). The mean differences between actual height and instrument height and standard deviations of the differences for the instruments examined by Hunt and Warren are shown in table 2. Those mean differences and standard deviations obtained by the Barr and Stroud dendrometer are

Table 2.--*A summary of results obtained from several tests of tree height measuring instruments*

Instrument	Number of measurements	Mean difference[1] (instrument-actual)	Standard deviation of differences
		Feet	
Abney level (Warren)	225	0.369	1.76
Haga altimeter (Warren)	225	- .144	1.91
Blume-Leiss altimeter (Warren)	225	- .319	1.93
Haga altimeter (Hunt)	351	.29	1.22
Engineer's hypsometer (Hunt)	351	- .11	1.60
Abney level (Hunt)	351	- .26	1.62
Spiegelrelaskop (Hunt)	351	.38	1.51
Barr and Stroud dendrometer	72	.378	1.66

[1]Actual height is for Warren's experiment, a taped measurement obtained by climbing; for Hunt's experiment, a height measured with a transit; and for the Barr and Stroud dendrometer, a taped measurement after felling the tree.

shown for comparison. Table 2 does not show statistical significance of these differences, but practical significance can be judged from the magnitude of the figures. All mean differences are less than one-half foot in absolute value and all standard deviations of differences are between 1 foot and 2 feet. Furthermore, so far as the dendrometer measurements are concerned, no correlation was found between measurement error and tree height. In other words, tall trees can be measured as accurately as short trees.

If it is not correlated with height, an average measurement error of less than one-half foot in tree height will introduce little bias into tree volume estimates.

Fitje (1967) reported tests of several height measuring instruments in Norway, the Blume-Leiss altimeter, the Suunto clinometer, and an instrument called the Meridian, which are capable of about the same degree of accuracy. Some observers detected no bias in height measurement. In other cases, a bias as large as 0.35 meter was discovered. The standard deviations of differences between instrument height and actual height ranged from 0.4 to 1 meter. Neither bias nor error was found to be correlated with tree height. In some instances, Fitje's experiment shows somewhat less accuracy for the instruments tested than do tests conducted by Hunt and Warren. However, the most accurate observers obtained results comparable to those in table 2.

There seems to be little difference in accuracy and precision between the Barr and Stroud dendrometer and some of the other instruments generally used for measuring tree height. However, table 2 can be misleading. The comparison shown is between the dendrometer in use in generally steep and brushy terrain and other instruments used under carefully controlled conditions in selected stands on level or nearly level ground. Much of the error in height measurement with instruments like the Abney level is the result of inaccuracy in measuring horizontal distance or slope distance from the observer to the subject tree. On level terrain, as in Hunt's and Warren's tests, distance measurement may not be too difficult, but on steep or broken ground where heavy underbrush makes clearing a 100-foot path to every tree expensive, an error of several percent in distance measurement is not surprising. Slope distance to the tree top calculated from dendrometer readings may be more accurate under such circumstances.

If measurements of tree height taken with the Barr and Stroud dendrometer are unbiased, then bias observed in dendrometer volume estimates must arise from some other source.

Tree Volumes Based on Dendrometer Measurements

Expected Effect of Bias and Error in Diameter Measurement

The proportional bias in diameter measurement, 1.19 percent more than the corresponding calipers measurement, is greater for most trees than the constant bias of 0.078 inch discovered in comparisons of taped d.b.h. measurements. To avoid underestimating the effect of diameter measurement bias on calculated volume, the larger bias is used. To assess the effect of bias, it can be assumed that Huber's formula is a satisfactory model for tree stem sections. Then, cubic volume in the ith section of the bole is:

$$v_i = k\, d^2_i l_i$$

where

v_i = cubic volume in the ith section

d_i = midpoint diameter of the ith section

l_i = length of the ith section

k = $(\pi/4)/144$.

Now, if all stem sections have the same length, total cubic volume in the tree is given by:

$$\sum v_i = k\,l \sum d_i^2$$

If the diameter measurements used are actually 1.19 percent larger than they should be and section length is unbiased

$$\sum v_i' = kl \sum (1.0119 d_i)^2$$

$$= kl\ (1.0239) \sum d_i^2$$

and

$$\sum v_i' / \sum v_i = 1.0239$$

indicating an expected bias in volume measurements of 2.39 percent.

In theory, cross-sectional stem area, hence volume, will also have a component of bias resulting from the random error associated with diameter measurements.

If

$$D_d = 1.0119\ D_a + \varepsilon$$

where

D_d = dendrometer diameter

D_a = actual diameter

ε = a random error with $E(\varepsilon) = 0$ and $E(\varepsilon^2) = \delta^2 D_a^2$ (Variance about regression is proportional to D_a^2)

then

$$D_d^2 = (1.0119\ D_a + \varepsilon)^2$$

$$= 1.0239\ D_a^2 + 2.0238\ D_a \cdot \varepsilon + \varepsilon^2$$

and

$$E_\varepsilon(D_d^2) = 1.0239\ D_a^2 + 2.2038\ D_a \cdot E_\varepsilon(\varepsilon) + E_\varepsilon(\varepsilon^2)$$

where E_ε denotes expectation with respect to the random variable ε. Since the expected value of ε is zero,

$$E_\varepsilon(D_d^2) = 1.0239\ D_a^2 + \delta^2 D_a^2$$

with $\delta^2 D_a^2$ being the additional component of bias. As given previously, estimated δD_a is about 0.2 inch for a 30-inch tree; or

$$0.2 = \delta \cdot 30 \rightarrow \delta D_a = 0.00667\ D_a$$

so that

$$\delta^2 D_a^2 = 0.000044\ D_a^2.$$

Though theoretically present, this component of bias is trivial and can be disregarded.

Effect of Bias in Height Measurement on Volume Measurement

Tree volume is nearly proportional to height. Thus, a 2 percent bias in height measurement, for example, would be carried through as 2 percent bias in volume measurement if it were evenly distributed throughout the tree stem. A constant height bias would lead to a larger volume bias for larger trees, but a smaller percentage of total volume, because it would be multiplied by a larger average cross-sectional stem area.

Where no bias is found in dendrometer height measurements, it can be inferred that there will be no nonrandom influence on volume measurement.

Comparison of Dendrometered Volumes (Outside Bark) With Volumes Measured After Felling

For 2 of the 78 trees measured with the dendrometer and subsequently felled, large differences between the two kinds of volume measurement obviously resulted from mistakes. The remaining 76 trees ranged in volume (felled tree measurement) from 2.6 to 380 cubic feet. Four dendrometer height measurements were not as accurate as the others. However, mistakes in height measurement apparently occurred in the topmost sections where they had little effect upon total tree volume; so the trees were allowed to remain in the sample because the value of the information contributed exceeded any possible distortion of results.

A preliminary regression of dendrometered volumes on felled tree volumes showed that variance about the regression line was proportional to the square of the independent variable, actual volume. Also, the estimated regression intercept was not statistically different from zero. A linear relationship passing through the origin of coordinates can be expected from this kind of data. The properly weighted regression conditioned to pass through the origin was:

$$\hat{V}_d = 1.05425\ V_f$$

where

V_d = estimated tree volume measured with the dendrometer

V_f = tree volume measured after felling.

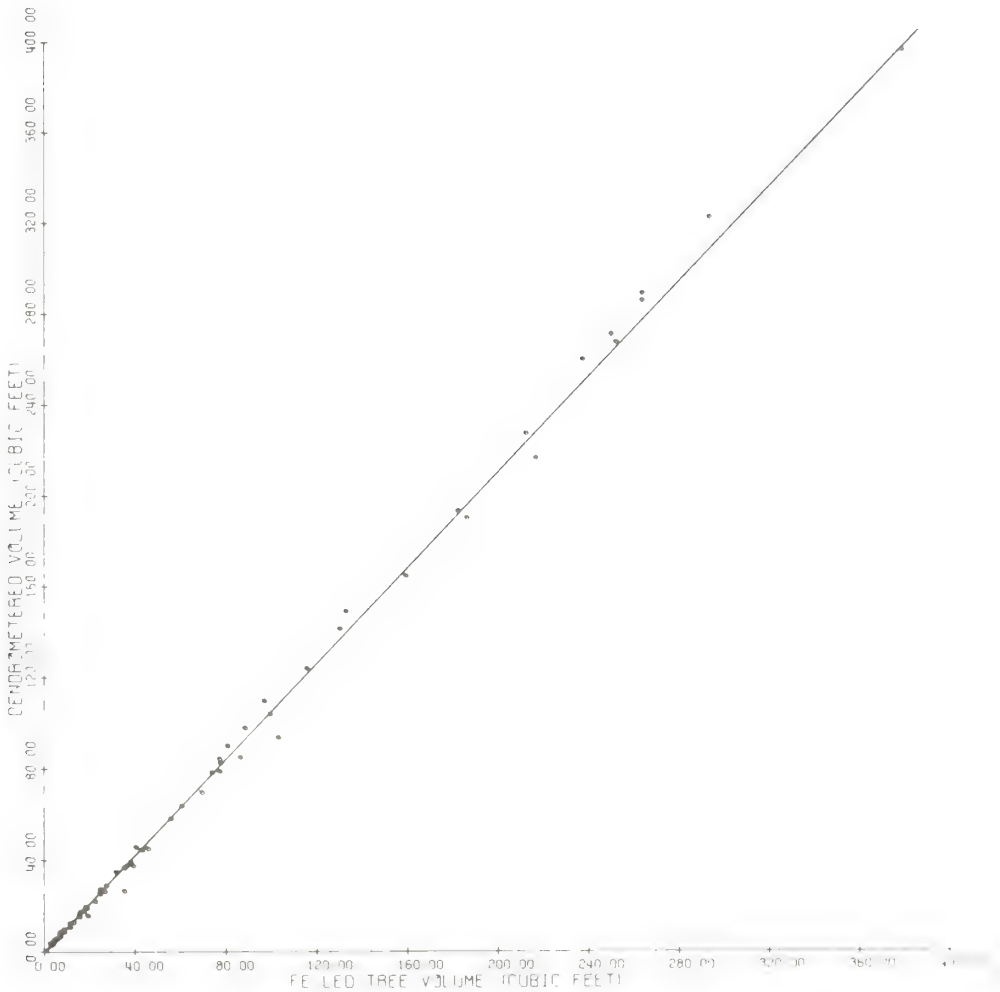


Figure 9.--Dendrometered volume plotted over felled-tree volume, with the fitted regression line.

This relationship is shown in figure 9. The estimated standard error of the regression coefficient (S_b) was 0.0088. The sample coefficient of correlation between the two kinds of volume measurements was 0.9974. The weighted root mean square residual about the regression was 0.606 cubic foot. However, this is a rather meaningless statistic when variance is not homogeneous. The standard deviation of residuals for various tree sizes as computed from the relationship between variance and tree volume is:

Tree volume *Cubic feet*	*Standard deviation of residuals*
10.0	0.30
50.0	1.52
100.0	3.04
150.0	4.55
200.0	6.07
250.0	7.58
300.0	9.11
350.0	10.62
400.0	12.14

Standard error is about 3 percent of tree volume, which agrees substantially with results of Grosenbaugh (1963) and Arvanitis (1968).

The regression coefficient of 1.05425 indicates an average positive bias in dendrometer volume measurements of 5.4 percent Even if twice its standard error is subtracted from the coefficient to obtain the coefficient's lower probable bound, a bias of 3.7 percent remains. This bias is greater than previous findings would have suggested; diameter measurements above breast height may carry a larger bias than those taken near the bottom of the tree. Often points on the upper stem are farther from the observer, but in steep terrain this is not always so. Whenever possible in this study, the technician located the dendrometer uphill from the tree being measured to get a better look into the crown and to avoid having to move the instrument. Bell and Groman (1968, 1971) found that the dendrometer overestimated smaller diameters by 0.06 inch and larger diameters by 0.04 inch. Presumably, the smaller diameters were those nearer the treetops. But this slight difference can by no means explain the apparent bias discussed here. Furthermore, most volume is in the lower portion of a tree, so inaccuracy in measuring topmost diameters would have a relatively small effect on volume measurement. The explanation offered by Gofas (1967) for overestimating tree volumes with the Bitterlich Spiegelrelaskop does not apply in this case. Unlike the Spiegelrelaskop, which uses a single distance measurement, the Barr and Stroud dendrometer measures slope distance to each point of measurement by the same true coincidence reading as is used in measuring diameter. This slope distance is used to calculate height, thus avoiding Gofas' problem of a diameter measurement taken at a lower height on the tree than that to which it was attributed.

Probably, about half of the 5.4 percent bias that appears in this comparison actually exists; the other half may result from the way in which dendrometer measurements and felled tree measurements were used to calculate tree volume. The NETVSL computer program uses Smalian's formula to compute volume of all tree sections above the stump. Smalian's formula gives reasonably accurate results for segments in the middle portion of the bole, but usually grossly overestimates volume in the butt portion. Dilworth (1961) showed the magnitude of errors that can be expected from Huber's, Smalian's, Rapraeger's, and Sorenson's formulas. His information is summarized in table 3.

Barnes (1945) reported that Smalian's formula gave an overestimate of 10.8 percent for cubic volume in butt logs of western hemlock. Most forest mensuration texts recognize that a truncated paraboloid is not a satisfactory model for the lower portion of a tree stem. Usually, a neiloid is suggested; however, Bruce (1970) has shown that it, too, is inadequate. He had good results with an equation that corresponds to a composite solid comprised of a cylinder with the diameter of the small end and a concave solid of revolution resembling a truncated conoid. Spaeth and others (1952) indicated that overestimates from Smalian's formula may not always be confined to the butt section of trees. In their experiment, Smalian's formula gave volume estimates for fenceposts 7 feet long that averaged 6 percent larger than volumes measured by displacement of water in a tank. Grosenbaugh (1966) emphasized that trees are not simple geometric solids; therefore some error must be expected from formulas based on simple models. He suggested that such error can be kept within acceptable limits by keeping measurement intervals on the stem short enough so that diameter at the small end of a stem section is more than 0.8 the diameter at the large end.

Aside from the way in which cross-sectional stem area was calculated, which caused but little difference, both dendrometer measurements and felled tree measurements were used to calculate volume in exactly the same way. So both sets of volume measurements would be expected to contain some positive bias because of the formula. Bias is not of the same magnitude for both kinds of measurements because stem measurements taken with the dendrometer were generally more widely spaced on the tree stem. Wider spacing of measurements with the dendrometer was caused partly by the observer's inability to see stems through the tree crowns in many places, and partly by his desire to measure as many trees as possible in a day without fully realizing the effect of wider spacing on accuracy.

Table 3.--*Total cubic-foot volume differences: four formulas*[1] *compared with Newton's formula; differences expressed as a percentage of volume computed by Newton's formula. From Dilworth (1961)*

Log group	Formula			
	Huber's	Smalian's	Rapraeger's	Sorenson's
		STUDY I (DOUGLAS-FIR)		
Butt	-4.9	+9.9	-0.1	-4.5
Intermediate	-0.8	-1.6	-6.2	-10.6
Top	+0.6	-1.4	-16.3	-22.1
Weighted average	-2.9	+5.8	-4.7	-13.8
		STUDY II (WESTERN HEMLOCK)		
Butt	-5.6	+11.2	+0.5	-2.7
Intermediate	+0.5	-1.0	+0.3	-3.7
Top	-2.1	+4.4	-23.0	-28.6
Weighted average	-2.2	+4.4	-1.4	-5.2

[1]Huber's formula: $V = \frac{\pi}{4 \cdot 144} D_m^2 L$

Smalian's formula: $V = \frac{\pi}{4 \cdot 144} \frac{(D_\ell^2 + D_s^2)}{2} L$

Rapraeger's formula: $V = \frac{\pi}{4 \cdot 144} (D_s + \frac{L}{16})^2 L$

Sorenson's formula: $V = \frac{\pi}{4 \cdot 144} (D_s + \frac{L}{20})^2 L$

Newton's formula: $V = \frac{\pi}{4 \cdot 144} \frac{(D_\ell^2 + 4D_m^2 + D_s^2)}{6} L$

where

D_s = diameter at the small end of the stem section
D_ℓ = diameter at the large end of the stem section
D_m = diameter at the middle of the stem section
L = section length
V = cubic volume

Young (1967) and Young and others (1967) reported results of an experiment in which volumes of felled trees were calculated with Smalian's formula using stem measurements spaced 8 and 16 feet apart. Volumes regarded as correct were measured by immersing tree pieces in a tank and measuring the amount of water displaced. Table 4 summarizes their results. Spacing measurements 16 feet apart lead to volume measurements that ranged from 3.8 to 15 percent greater than those obtained by a measurement spacing of 8 feet.

In the study reported here, a bias of about 2.4 percent in dendrometer volume measurement was expected because of bias in diameter measurement. An apparent additional bias of 3 percent was found by comparing dendrometer volume measurements with felled tree measurements. Bias probably was introduced by improper use of Smalian's formula in the volume computation program and by spacing dendrometer measurements

Table 4.--*A comparison of tree volumes computed by Smalian's formula with volumes measured by water displacement. From Young and others (1967)*

Species	Computed volume as a fraction of water displacement volume		Ratio
	8-foot sections	16-foot sections	
Spruce	0.997	1.035	1.038
Fir	1.032	1.096	1.061
Hemlock	1.035	1.102	1.065
White pine	1.003	1.042	1.039
Cedar	1.072	1.234	1.151

farther apart on the tree trunk than measurements taken after felling. This apparent 3 percent bias is not as great as that shown for most species by Young and others (1967) (table 4) because dendrometer measurements were generally more than 8 feet and less than 16 feet apart.

Cost (1971) supported the conclusion that actual bias in dendrometer volume measurements is little more than would be expected from the 1.19 percent bias in diameter measurement. In his trial of the McClure mirror caliper, two of his observers obtained independent total volume estimates for 25 trees that were within 2.1 percent of the total volume measured after felling. Accuracy was obtained by taking measurements at intervals of only 4 feet in the sawlog portion of the tree and at intervals of 5 feet above the sawlog portion. With measurements so closely spaced, the effect of using an inappropriate geometric model is reduced to an acceptable level.

EVALUATION OF THE BARR AND STROUD DENDROMETER, OTHER OPTICAL INSTRUMENTS, AND FELLED TREE MEASUREMENT

If use of an optical instrument to measure tree volumes is decided upon, the following instruments are available in the United States:

The Barr and Stroud dendrometer, Model F.P. 15;

The Universal Teledendrometer (UTD) (Fricke 1967);

Bitterlich's Relaskop (Bitterlich 1952), Wide Scale Relaskop (Sutter 1965), and Tele-Relaskop, a fairly recent improvement of the relaskop which uses a telescope to magnify the tree image;

Wheeler's penta prism optical caliper (Wheeler 1962); and

The Todis dendrometer.

Two other instruments, not in commercial production but obtainable by special order, are the McClure mirror caliper (McClure 1969) and Mesavage's modified Teletop dendrometer (Mesavage 1969b).

A choice between various instruments (for reasons other than cost) will be based on:

1. Size of trees to be measured

2. Level of accuracy desired, the number of measurements desired, or the purpose for which they are taken

3. Relative productivity of the several measurement techniques in terms of number of trees measured per hour or day, and

4. Restrictions on felling sample trees.

Measurable Trees

The tabulation shows the largest diameter measurements[2] that can be taken with several different instruments:

Barr and Stroud	200 inches
Universal Teledendrometer	24 inches
Bitterlich's wide scale relaskop[3]	±20 feet
Wheeler penta prism caliper	34 inches
McClure mirror caliper	32 inches
Mesavage's modified Teletop	36 inches
Todis dendrometer (direct reading)	31.5 inches
Todis dendrometer (with prisms)	110.2 inches

Although the UTD can measure diameters as large as 24 inches, it must be located exactly 100 feet from the place on the tree stem being measured to do so. This distance requirement severely limits the instrument's usefulness. Mesavage (1969b) and McClure (1969) described ways in which measurement capacities of their instruments could be increased. Unfortunately, the rapidity and simplicity of measurement, advantages of the Teletop and mirror caliper, decrease sharply when extraordinary steps are taken to measure large diameters. In addition, steps involved are likely to cause measurement errors. The Todis dendrometer can measure diameters as large as 31.5 inches without special prisms to make measurement of larger stems possible.

Provision for Height Measurement

If a dendrometer is used to measure standing tree volume, it is necessary to measure not only diameter at various points on the stem but height to points of measurement as well. Only in this way can the length of stem sections be obtained for volume calculation.

Optical Calipers and the Relaskop

Instruments such as the penta prism and mirror calipers measure diameter only. When using these instruments, height must be measured by some independent means. The Forest Resources research unit of the USDA Forest Service in the southeastern States uses sectional aluminum poles, marked at every foot, that stand parallel to the tree bole. Diameter can then be measured with a mirror caliper and the height to that point read from the adjacent pole. The observer is free to move to any position that offers an unobstructed view of the tree. McClure (1968) claimed that under ideal conditions such poles can be extended as much as 120 feet above the ground. Under less than ideal conditions, an extension of 80 feet may represent a more practical limit. Another arrangement involves attachment of a clinometer to the optical caliper. The clinometer is then readily available for measurement of the angle above the horizontal plane. In using the clinometer, it is necessary to measure the distance from the observer's position to the tree, which cannot be done with the caliper.

To measure height with any variant of the Bitterlich relaskop, one must either measure distance from the tree with a tape and use the relaskop to obtain angles above and below the horizontal or use a vertical base of known length beside the tree.

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[2]In some cases larger measurements can be taken by complicating the measurement process.

[3]For the same distance between tree and observer, the conventional relaskop and Tele-Relaskop cannot measure as large a tree as the wide scale relaskop. Since the relaskops are optical forks, one cannot specify an absolute maximum measurement.

Rangefinder Dendrometers

The UTD measures height with an awkward scale arrangement that reproduces angles and distance to the base and upper points on a tree stem. Slope distance from the instrument to the point of measurement is obtained with the Teletop rangefinder.

Mesavage's modified Teletop dendrometer measures slope distance in the same way, but necessary angles are measured with an Abney level or clinometer attached to one side of the dendrometer.

The Barr and Stroud dendrometer is equipped with an inclinometer from which the user reads the sine of the angle formed by the line of sight and the horizontal plane. Distance between the tree stem and the instrument along the line of sight is measured by the dendrometer's rangefinder.

The Todis dendrometer measures the angle to the point of measurement to the nearest 10th of a degree.

Accuracy of Rangefinder Dendrometers

Use of a clinometer or Abney level to measure tree height usually involves measurement of a single distance between the tree and the observer. In heavy brush and on steep slopes, this measurement can be quite inaccurate. Distance to the tree is used with the tangent or cosine of the angle of elevation or depression to compute the height of the point of measurement above or below the horizontal plane. It is assumed that the tree is vertical. If it is not, errors in height measurement will differ in direction and magnitude according to the direction and amount of lean. Inclination of the tree perpendicular to the line of sight will lead to a biased measurement, as will lean parallel to the line of sight. When measuring poles are not used, this method of height measurement must be employed with the penta prism or mirror calipers and with the Bitterlich relaskop.

On the other hand, the Barr and Stroud dendrometer, the UTD, Mesavage's modified Teletop dendrometer, and the Todis dendrometer use the sine of the angle of elevation or depression with the measured slope distance from the instrument to the tree bole at each point of measurement. The tree is assumed to be vertical in this case also, but it can be shown that the bias in height measurement resulting from lean parallel to the line of sight is less than the bias resulting from the clinometer method. With rangefinder dendrometers, the component of a tree's lean that is perpendicular to the line of sight does not affect accuracy of height measurement. The halving line that splits the tree image must be oriented squarely across the stem. For this reason, the angle of elevation is not truly a vertical angle. It is turned in a plane parallel to the tree stem; therefore, it measures the length of the tree rather than height above the horizontal plane. Although most computation techniques do not do so, all measurements necessary to compute stem section length from two distance measurements and an angle are provided by the rangefinder dendrometers. Consequently, lean in either direction is immaterial.

Instrument Readings

Barr and Stroud Dendrometer

The measurements read from the Barr and Stroud dendrometer are the true and false coincidence settings of its rotating prisms. With the use of the manufacturer's tables, charts, or a slide rule approximation (Bruce 1967a; Mesavage 1965; Mesavage 1968), such measurements can be converted to range and diameter in the field. In order to spend all available field time measuring trees, workers do not usually make these conversions. The coincidence readings and sine of the angle of elevation are recorded

for each measurement point on each tree and diameters, heights, and volumes are computed in the office. For this reason, coincidence readings are not meaningful to the instrumentman. Consequently, readings that would be questioned if they were read directly as diameters may go unnoticed until it is too late to correct them. However, even though the numbers themselves are meaningless to the observer, a reading that does not conform to the general trend of coincidence readings for a particular tree can often be detected and checked.

Bitterlich's Relaskop

The Bitterlich relaksop and Tele-Relaskop are read in relaskop units, which are proportional to diameter. The constant of proportionality varies for different distances to the tree; so suspicious readings can be detected only by comparison with other readings taken from the same instrument location.

Direct Reading Instruments

Dendrometers based on the Zeiss Teletop, the McClure and Wheeler optical calipers, and the Todis dendrometer are read directly in inches or centimeters for all but large trees. Each reading can be compared immediately to the next lower measurement. The optical calipers can also be used to locate the height at which the tree bole has a given diameter, providing the bole is visible at that point. For example, if 7 inches outside bark is considered the upper limit of merchantability, the instrument can be preset at 7 inches. Then, the user can search up and down the tree until the correct image alinement is obtained. To locate the specified upper limit of merchantability with the Barr and Stroud, several measurements would be required, a trial and error scheme that would be highly impractical.

Tree Stem Image

The McClure mirror caliper, the Wheeler penta prism caliper, and the Bitterlich relaskop are all without image magnification. The Barr and Stroud dendrometer is provided with 5.5 magnification and the Zeiss Teletop, upon which the UTD and Mesavage's modified Teletop dendrometer are based, gives 6 magnification. The Tele-Relaskop offers 8 magnification and the Todis 6.

There are two important advantages to be obtained from image magnification. With magnification, alinement of the half-images for true and false coincidence or reading a relaskop scale can be much more precise. Who can really presume to aline two half-images within one-tenth of an inch at a distance of 200 feet? It is much more probable that this could be done at a distance of 36 feet, which would be the result of 5.5 magnification. If the small bias of the Barr and Stroud in diameter measurement discovered in this study and previously reported by others is indeed due to a characteristic of human vision, magnification could be expected to reduce the effect. Tests of the McClure and Wheeler optical calipers, unsupported by staff or tripod (Robbins and Young 1968), failed to show bias, probably because of a fairly large associated variance in measurements. The optical caliper measurements reported consistently exceeded those of mechanical calipers by about 0.2 inch. Robbins and Young (1968) reported no statistically significant improvement in precision when a 2X lens was attached to the Wheeler caliper. They attributed this to limited magnification and lack of rigid instrument support. Greater magnification and use of a Jacob's staff should increase caliper precision without seriously increasing its weight or hampering its ease of use.

The second advantage of magnification is due to the well-known light gathering properties of an objective lens. On a dull, overcast day, it is often dark under a dense stand of trees. It is even darker when one is looking into tree crowns. Magnification gives a brighter, more sharply defined image than can be obtained by the unaided eye.

On the other hand, ordinary spectacles prevent about 8 percent of the light received from reaching the eye of the wearer (William B. Durbon, O.D., personal communication). It seems likely that two penta prisms would absorb considerably more light; so the right-hand image seen through a penta prism caliper would be far less bright than the tree stem viewed with the naked eye. Under poor light conditions, this could be a serious disadvantage. Light transmission qualities of the mirror caliper are better for the displaced image because two, rather than three, reflections are involved and light does not pass through glass.

Even though the Teletop provides 6 magnification, the writer found in a limited field trial that its image is considerably less bright than that of the Barr and Stroud. In the UTD, the tree image is inverted. Seen through Mesavage's modified Teletop, the image is not inverted, but the right and left sides are transposed. Mesavage (1969b) mentioned these disadvantages in comparing the correctly oriented Barr and Stroud image. Unwanted reflections sometimes appear in the Teletop's field of view and hinder adjustment of false coincidence.

Measurement Time

About the same amount of time is required to take a diameter measurement on the tree bole with the penta prism and mirror calipers, according to Robbins and Young (1968). In his time study of tree measuring instruments, Pfeiffer (1967) found that the time required is about one-third that necessary with the Barr and Stroud dendrometer and the Bitterlich relaskop. This finding makes it appear that more measurements in the same period of time might make up for the lower precision of the two optical calipers. Further, each diameter measurement can be taken from a different position on the ground. It becomes cumbersome to use more than two instrument locations for the same tree when using the Barr and Stroud, the UTD, and the modified Teletop dendrometer.

However, when volume calculation requires that height be recorded at each point of measurement, the rapidity of optical caliper use disappears. So long as measuring poles are not used, a hyposometer of some kind and a distance measurement are needed to measure height. If the observer wishes to make only one measurement of distance, he will have to forego the advantage of being able to use a different instrument location for each measurement. Whether the clinometer is attached to the optical caliper or not, the height measurement will be an entirely separate operation unless both instruments are used with a tripod or Jacob's staff. Without such support the possibility of mistakes exists because the height may be measured to some point on the stem different from the point at which diameter was measured.

The Bitterlich relaskops require either a new distance measurement or a new observation of the vertical reference rod each time the instrument is moved to a new location

To measure vertical angles, the UTD must be leveled each time it is set up. Leveling is not necessary with the Barr and Stroud or the modified Teletop, because the inclinometer itself is leveled with a bubble at each observation.

Table 5 shows the readings for the seven instruments that must be available for each stem measurement in order to calculate the volume of a tree. Note that unless height measuring poles are used, each instrument requires that at least three items be recorded. Even though distance from the observer to the tree needs to be measured only once so long as instrument location does not change, that measurement can be time consuming and results often inaccurate.

After considering the time study information available in the literature and the number and kind of measurements required for volume calculation, other dendrometers currently in use do not appear to be materially more productive in terms of trees

Table 5.--*Showing the instrument readings which must be recorded at each point of measurement for purposes of volume calculation*[1]

Reading	Barr and Stroud	Wheeler penta prism caliper	McClure mirror caliper	Bitterlich Relaskop[2]	Universal Teledendrometer	Modified Teletop	Todis[3]
Diameter		N	N		N	N	A1
Range (slope distance to stem at point of measurement)					N	N	
Angle of elevation or depression (or a function thereof)	N	A1	A1	A1 A2	N	N	A1 A2
True coincidence reading	N						A2
False coincidence reading	N						A2
Single distance measurement (taped)		A1	A1	A1			
Angle subtended by vertical rod					A2		
Relaskop units					N		
Reading from measuring pole		A2	A2				

[1]N denotes items that are absolutely necessary.
[2]Including the Wide Scale Relaskop and the Tele-Relaskop.
[3]A1,A2 denote items that are necessary under the first or second of two reasonable alternatives.

measured per hour than the Barr and Stroud. Where trees are fairly small, use of a height-measuring pole with mirror or penta prism calipers is an exception to this generalization.

Dendrometer Disadvantages

Low underbrush may not be a serious problem, since measurements at breast height and lower on the tree can be taken with a diameter tape or mechanical calipers. High bushes, the trunks and branches of other trees, and branches of the subject tree itself can seriously affect measurements of the upper portion of a tree's stem. Use of Smalian's formula usually results in overestimates of stem section volume and Huber's formula in underestimates. If stem section length is kept short enough, inadequacy of the geometric model may not introduce a serious bias. In a dense stand or when dealing with dense-crowned species, it is often difficult to keep stem sections short. Also, much time can be spent finding an instrument location that offers the best possible view of the tree stem.

Usually, tree volume inside bark is of primary importance. Measurements with any dendrometer necessarily include the bark and so must be corrected by deducting estimated bark thickness. In most cases, this estimate will be obtained from a predicting equation of one sort or another (Mesavage 1969c; Brickell 1970b). Still, the error and bias in bark thickness estimation will contribute to total error and bias in measurements of tree volume inside bark because even the best regression predictions are subject to some error.

Comparison of Standing Tree Measurement With Felled Tree Measurement

If sample trees can be cut, felling generally is the best practice. On the ground, the entire stem can be measured at any point. Section measurements can be short to assure accuracy of computed volume. Bark thickness can be measured wherever diameter is measured. Furthermore, any desired stem analysis information is available. Dissection of felled sample trees allows calculation of gross, cull, and net volume.

Experience on the Kootenai National Forest has shown that the average assortment of trees (other than ponderosa pine) up to 30 inches d.b.h. can be felled, bucked into 8-foot sections, and measured for gross, cull, and net volume nearly as quickly as they can be measured with the Barr and Stroud dendrometer. Larger trees are more rapidly measured with the dendrometer. Figure 10 illustrates relative rates of felling and dendrometer measurement. Naturally, when cull volume is being measured, it takes longer to measure felled trees with defects than those without. If gross volume only is to be measured, the measurement rate in felled trees will compare even more favorably with that attained by the dendrometer.

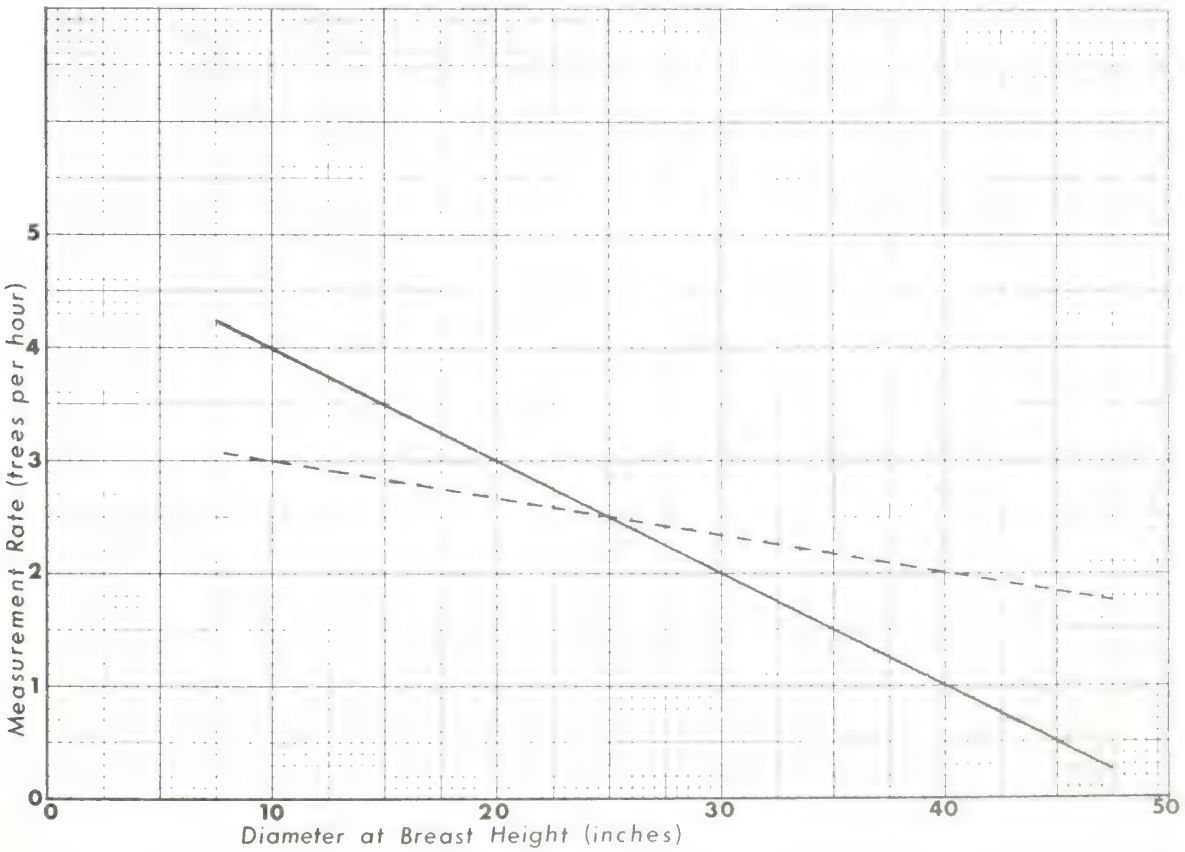

Figure 10.--The general relation of measurement rate to tree size. Felled trees are shown by the solid line; dendrometered trees by the dashed line.

A suitable chain saw and other such necessary equipment as fuel, oil, file, chain wrench, axe, and felling wedges will weigh more than the Barr and Stroud dendrometer, its protective case, and tripod. But, more precautions must be taken to protect the dendromter. Not only is the dendrometer more susceptible to damage than a chain saw, but once damaged or shaken out of adjustment, it will probably have to be sent to Scotland for repairs. On the other hand, chain saw repair shops can be found in almost all forested areas in the United States.

Measurement of Upper Stem Diameters for Purposes Other Than Direct Volume Measurements

Form Class or Form Quotient Estimation

Form class volume tables are often used with an inaccurate estimate of form class. Form class tables are seldom entered with an accurately measured form class for each tree. But, by doing so, Hartman (1967) showed an increase in cruise accuracy on Bureau of Land Management timber sales.

If the accuracy required of a cruise warrants individual form class measurement, use of a dendrometer would be the best way to obtain the upper diameter measurement. For this purpose, the Barr and Stroud, the Todis, and instruments based on the Zeiss Teletop apparently are not as satisfactory as either the mirror caliper or the penta prism caliper. If trees are too large for these instruments, Bitterlich's relaskop could be used. Height measurement is not a concern here because a telescoping pole or one cut in the woods can be used to mark the top of the first log. Aside from their lower cost, advantages of optical calipers for this purpose are that they are light-weight, portable, and are quick and easy to use. Two measurements can be taken from different positions in less time than would be required for one measurement with the Barr and Stroud. Judson (1964) reported that Girard form class can be estimated quite precisely from the ratio of diameter outside bark at the top of the first log to d.b.h. plus double bark thickness at breast height.

Bonner (1968) showed that the ratio of diameter halfway up the tree to d.b.h. in a tree volume prediction equation reduces the standard error of estimate by more than 30 percent. Value of this form quotient was recognized in the last century by Schiffel, Kunze, and Schuberg (Spurr 1952), but instruments for measuring upper diameters were not as precise as those today. Both optical calipers are more satisfactory than the rangefinder dendrometers for measuring diameter at the tree's midpoint. For diameters beyond the capacity of the optical calipers, the Bitterlich relaskop can be used. Stem midpoint can be easily located by averaging slope percent readings taken at the base and tip of a tree with a clinometer. To do this with the sine of the angles would be a more involved and time-consuming process.

Merchantable Length

Locating a specific diameter requires an instrument that can be preset for that diameter. This requirement virtually prohibits practical use of the rangefinder dendrometers unless they are used as optical calipers. To use the relaskop, the desired instrument reading in relaskop units would have to be calculated after measuring horizontal or slope distance to the tree. Distance must be measured in order to measure merchantable stem length; so the required reading for any given distance and diameter limit could be read from a prepared chart. Since the diameter limit of merchantability is usually within the capacity of optical calipers, they would be well-suited to this use.

Growth Measurement

Research plots.--For measuring periodic growth of standing trees, precision at least equal to that of the Barr and Stroud is desirable in any optical instrument. Bias in measurement can be corrected; in the difference between two volume measurements, it might be largely self-correcting. However, a large standard error of the difference would make the periodic growth measurement for a tree unreliable, even if such error represented a small percentage of total volume. When a tree is to be remeasured with the dendrometer, the instrument location should be monumented and the height of the instrument recorded. Future measurements then can be taken at very nearly the same points on the tree by setting up the dendrometer at the same location and height and the inclinometer at the sine of elevation readings previously obtained. Some permanent plot measurement procedures were given by Groman and Berg (1971).

SUMMARY AND SUGGESTIONS

This study disclosed a positive bias of 1.19 percent in diameter measurement with the Barr and Stroud dendrometer. The dendrometer's tendency to slightly overestimate diameters had been reported by others, but bias may be caused by some characteristic of human vision. No bias was found in the measurement of tree heights. Diameter measurement bias could be expected to give an average volume overestimate of about 2.39 percent. A comparison of dendrometered volume with felled tree volume indicated that dendrometer measurements led to an overestimate of about 5.4 percent. This large overestimate may have resulted from using an inadequate geometric model to calculate lower tree stem volume and from wider spacing of dendrometer measurements. If a measurement process is precise, bias can often be removed or minimized by calibrating laboratory instruments.

Random error in volume measurements was found to be about 3 percent of tree volume, much less than the 12 or 15 percent usually associated with volume tables or equations.

For certain tree measurement purposes, the Barr and Stroud dendrometer is potentially a useful instrument. To obtain satisfactory accuracy and precision in field use, the following suggestions are given:

1. A technician assigned to take measurements with the dendrometer should be thoroughly trained in its use and given ample tree measurement experience in the training situation.

2. Any measurement bias peculiar to an instrumentman should be evaluated by a diameter measurement trial such as that described in this paper. If bias can be accurately estimated, it can be removed.

3. Much of the time required to measure a tree is spent finding an instrument location and clearing away brush that obscures the line of sight. The cost of additional stem measurements is small and is a direct investment in accuracy. Therefore, diameter measurements should be no more than 8 feet apart in the tree's lower portion.

4. Use of an adequate geometric model for bole segments is necessary for accuracy, regardless of the way diameter and length measurements are taken. For this reason, any computer programs used for the calculation of tree volumes should be revised, if necessary, so as to use suitable formulas for different portions of the bole.

5. The necessity of discarding a few incorrect observations from the data used in this study emphasizes the requirement of extreme care in reading and recording measurements taken with the Barr and Stroud dendrometer. Instrument readings recorded in the field are meaningless; so erroneous measurements may not be detected when they are taken. Slide rules designed by Bruce (1967a) and Mesavage (1968) can be used to check measurements while work is in progress. However, some of the newer hand-held, battery-powered calculators can be programed, and might be used to convert dendrometer readings to diameters and heights in the field more easily and more accurately than slide rules.

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APPENDIX A

Analysis of Data

The mean of the 87 calipered diameters was 17.68 inches. This figure can be compared with the means of dendrometer measurements shown in table 6 for the nine different (observer X instrument constant) combinations. At most, the means of dendrometer diameters differ from each other by 0.05 inch but they differ from the mean of caliper measurements by about 0.20 inch.

Table 6.--*Means of dendrometer measurements according to observer and instrument constants*

Observer	Instrument constants		
	Grosenbaugh's old set	Grosenbaugh's new set	Direct calibration set
	Inches		
P	17.88	17.86	17.88
B	17.88	17.86	17.88
R	17.90	17.88	17.91

The questions to be answered statistically were whether or not the dendrometer measurements differ significantly from caliper measurements on the same tree and, if so, whether or not that difference was the same for all nine sets of dendrometer measurements. The analysis of covariance technique was used for this purpose. At the same time, the regression of dendrometer diameter on caliper diameter can be used to evaluate any bias in dendrometer measurement and the error of dendrometer measurements after correction for bias. If no bias exists in dendrometer measurement, the regression expected is:

$$D_d = b_0 + b_1 D_c + \varepsilon$$

where

D_d = diameter measured with the dendrometer

D_c = diameter measured with calipers

$b_0 = 0$

$b_1 = 1$

ε = a random error with mean of zero.

If either or both of the coefficients b_0 and b_1 differ significantly from zero and unity, respectively, then bias is indicated in dendrometer measurements of diameter. The standard error of residuals about the regression provides an estimate of the error of dendrometer measurements after bias has been removed. For use as a standard of comparison in this experiment, caliper measurements of diameter have been considered without error or bias. Freese (1960) has recommended the use of a Chi-square technique for deciding whether or not a new instrument or method of measurement is sufficiently accurate for use when results are compared with those of a known standard. His Chi-square test compares mean square error (variance plus bias) to a predetermined acceptable error. However, even when the Chi-square technique is used in the presence of bias related to size of the standard measurements, the regression of test measurements on the known standard must be estimated if one wishes to separate bias from error. The decision regarding sufficiency of accuracy is then based upon the statistic:

$$\chi^2_{(n-2)\ \mathrm{df}} = \frac{\Sigma\ \mathrm{res}^2}{\sigma^2}$$

where

$\Sigma\ \mathrm{res}^2$ = the sum of squared residuals about regression

σ^2 = a required level of accuracy decided upon through practical considerations.

A computed Chi-square larger than the tabular value for $(n\text{-}2)$ degrees of freedom at the desired probability level would indicate insufficient accuracy of the instrument or technique. The regression of measurements being tested on the known standard preserves the distinction between bias of measurements and random error. The purpose of this analysis was to estimate the error and bias of dendrometer measurements, not to decide whether or not their magnitude should preclude use of the instrument. If one can state the level of accuracy his purposes require, the Chi-square test can be easily completed using the residual sum of squares given in this paper.

The analysis of covariance is standard technique for testing differences between several regressions, in this case, whether or not dendrometer bias or lack of bias differs between observers and between different sets of reasonable instrument constants Appendix B, the format of which was suggested by Freese (1964), shows the results of covariance analysis upon these data. Examination of the variance about the regression showed that variance was nearly proportional to D_c^2, the square of the independent variable. Therefore, all observations were weighted by a value proportional to $1/D_c^2$. The weights were scaled so that the sum of weights was equal to the number of observations. The sums of squares used in this analysis then were weighted sums of squares. The same weights were used for all regressions. It is apparent from appendix B that the variation explained by regression was increased only slightly by allowing each data set to carry its own intercept while forcing a common slope for all sets. An even smaller additional increase in explained variation was obtained by allowing a completely separate regression for each data set. The variance ratios (F statistics) obtained from the differences in residual variation did not even begin to approach the 5 percent significance level. The hypothesis that there is a common regression for three observers and three sets of instrument constants is not rejected. The common regression (appendix B, line 14) is:

$$\hat{D}_d = \hat{b}_0 + \hat{b}_1 D_c$$

where

$\hat{b}_0$ = -0.0024862

$\hat{b}_1$ = 1.0117607

r^2 = 0.998880.

Error statistics for this regression are:

S_{yx} = standard deviation of weighted residuals = 0.19 inch

S_{b_0} = standard error of b_0 = 0.01750789

S_{b_1} = standard error of b_1 = 0.00121211.

The t statistic used to test the difference of the intercept from zero is:

$$t = |\hat{b}_0/S_{b_0}| = |-0.0024862/0.01750789| = 0.14200152.$$

For 781 degrees of freedom t >1.96 is necessary to be 95 percent confident of a real difference. The hypothesis that the regression has a zero intercept is retained.

For testing the significance of difference between the regression coefficient and unity, the t statistic is:

$$t = (b_1 - 1)/S_{b_1} = 0.0117607/0.00121211 = 9.702758.$$

The value of t necessary to be 99.9 percent confident of a real difference is 3.29 for these degrees of freedom. Therefore, the regression coefficient apparently is different from unity.

Because the regression intercept most probably is not different from zero and because nothing inherent in the nature of the data precluded it, a regression constrained to pass through the origin was indicated. Variance of dendrometer measurements around the regression line was proportional to D_2^2 as before; so the regression coefficient was estimated from the weighted uncorrected sums of squares and cross products. With the weights used here, the regression coefficient becomes "the mean of ratios estimator." That is,

$$b_1 = \frac{\sum (D_1/D_2)}{n} .$$

Simple proof of this can be found in statistical texts (Deming 1928; Draper and Smith 1966; Freese 1964). For the regression, only data compiled with Grosenbaugh's exact instrument constants were used. These constants were slightly, though not significantly, better than the other two sets of constants. Although data obtained through three sets of instrument constants may not constitute independent observations, measurements taken by different observers were independent. This gives the regression:

$$\hat{D}_1 = b_1 D_2$$

where

b_1 = 1.0118866

r^2 = 0.99835

S_{yx} = 0.19 inch

S_{b_1} = 0.00081

A bias in dendrometer measurements of diameter in excess of 1 percent is indicated.

APPENDIX B

Analysis of Covariance

Regression of dendrometered diameters on calipered diameters; nine data sets (three observers X three sets of instrument constants). Observation weights are proportional to $(1/D_c^2)$. Weights are scaled so that sum of weights equals number of observations.

	Set[1]	df	Source	df	Residuals Sum of squares	Mean square
1	PDC	86	Individual regressions within data sets	85	3.1154812	
2	PGO	86		85	3.1178901	
3	PGN	86		85	3.0913137	
4	BDC	86		85	2.9911826	
5	BGO	86		85	2.9136870	
6	BGN	86		85	3.0146680	
7	RDC	86		85	3.1564934	
8	RGO	86		85	3.1911497	
9	RGN	86		85	3.0751897	
10			Total	765	27.6670555	0.03616608
11			Differences for testing slopes	8	.0707543	.00884429
12		774	Common slope, 9 levels	773	27.7378098	.03588332
13			Difference for testing levels	8	.0711811	.00889764
14		782	Common regression	781	27.8089909	.03560691

For test of difference in slopes $F_{8/765} = \frac{0.00884429}{0.03616608} = 0.24454645 \rightarrow$ NS @ 0.05.

For test of difference in levels $F_{8/773} = \frac{0.00889764}{0.03588332} = 0.24796032 \rightarrow$ NS @ 0.05.

[1]Data sets are identified by the observer's initial (P,B,R) and by the instrument constants used in compilation of the data. Thus, PDC means observer P's dendrometer readings compiled with direct calibration instrument constants (see table 1). BGO means observer B's readings compiled with Grosenbaugh's old constants, and RGN means observer R's readings compiled with Grosenbaugh's new constants.

Brickell, J. E.

1976. Bias and precision of the Barr and Stroud dendrometer under field conditions. USDA For. Serv. Res. Pap. INT-186, 46 p., 83 ref. Intermountain Forest & Range Experiment Station, Ogden, Utah 84401.

Information is presented and methods of testing the Barr and Stroud optical dendrometer in the field are described. Advantages and disadvantages of the Barr and Stroud compared to other means of tree measurement are discussed.

OXFORD: 521.1; 524.2.
KEYWORDS: diameter measurement, volume measurement (tree), tree measurement, volume measurement.

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AMERICAN REVOLUTION BICENTENNIAL
1776-1976

GROWING
FROM
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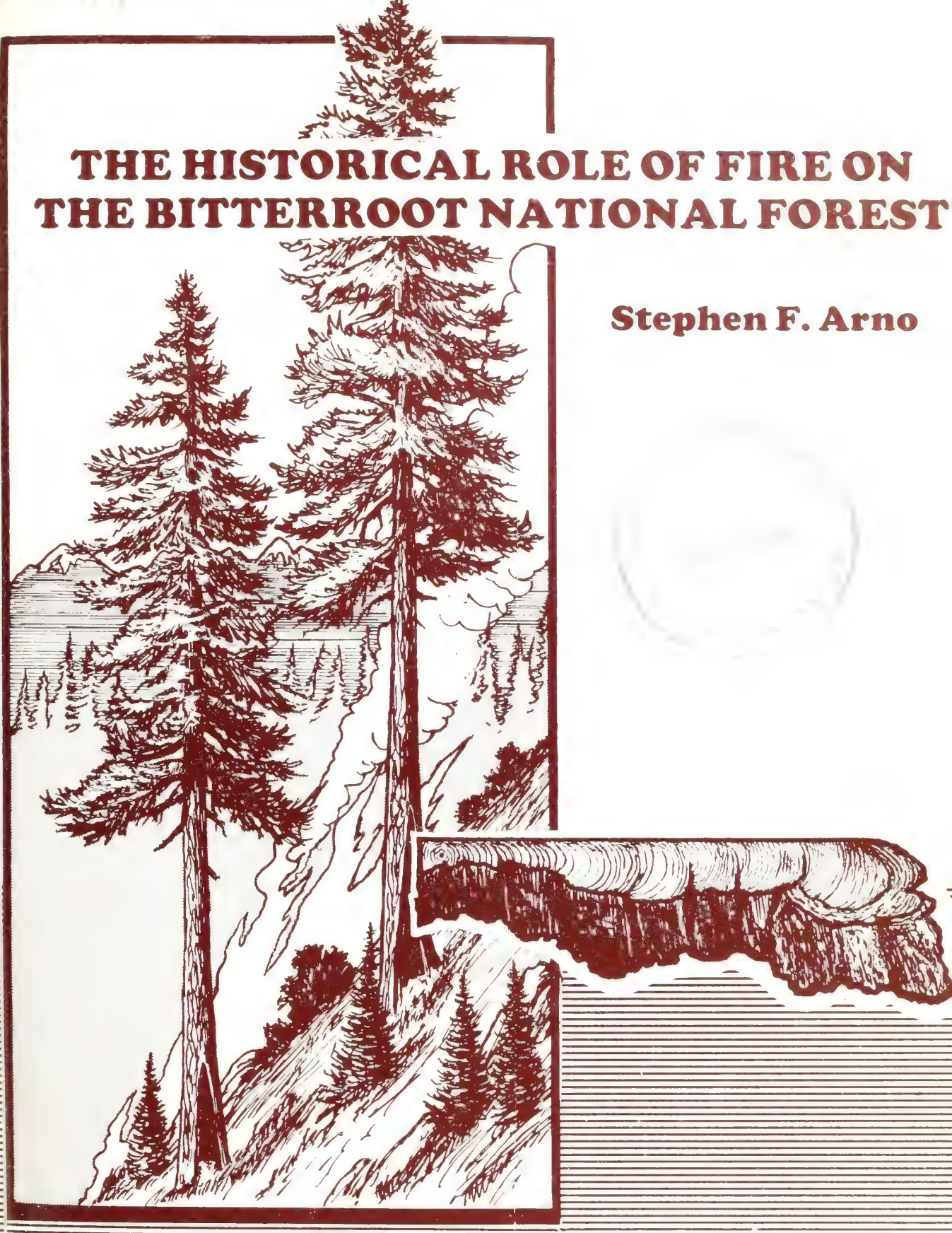
THE HISTORICAL ROLE OF FIRE ON THE BITTERROOT NATIONAL FOREST

Stephen F. Arno



USDA Forest Service Research Paper INT-187
INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION

THE AUTHOR

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THE HISTORICAL ROLE OF FIRE ON THE BITTERROOT NATIONAL FOREST

Stephen F. Arno

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
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ABSTRACT

Presents frequencies, intensities, and influences of fire on stand structure and composition on the Bitterroot National Forest in west-central Montana. Three study areas were established, each having a wide range of elevations and forest types. Findings are based upon study of nearly 900 individual fire scars on living trees, and on age-classes of shade-intolerant trees attributable to fire.

During the period from 1600 to 1900 fires were frequent in most habitat types, and substantial amounts of forest survived most fires. Some high-intensity stand-destroying fires were also detected in certain habitat types on each study area. Results show that fire was historically a major force in stand development, but that it has been of minor significance during the past 50 years, possibly because of organized fire suppression.

INTRODUCTION

Biologists have long recognized that fire historically has had strong influence on he ecology of Northern Rocky Mountain forests (Intermountain Fire Research Council 970; Habeck and Mutch 1973). However, there is little data on frequency and severity f fires in the various forest types before organized fire suppression evolved in the arly 1900's. Thus, questions and conjecture have arisen about the patterns and types f fires that occurred: highly destructive crown fires at long intervals or creeping round fires at short intervals. Confounding this problem are great differences among he types of forests found in this region (R. and J. Daubenmire 1968; Pfister and thers, in press) and probably among their respective "fire ecologies." A review of he literature dealing with fire in the Northern Rocky Mountains is provided by Wellner 1970) and is updated by Arno.[1]

The present study was developed to provide detailed information on historical fire n one small portion of the Northern Rockies. Specifically, the goal was to determine istorical frequencies, intensities, and influences of fire on stand structure and omposition in various forest types found on the Bitterroot National Forest in est-central Montana. A knowledge of the workings and results of the historical fire egime is an essential element in describing forest ecosystems, development of manage- ent alternatives, and planning subsequent programs and projects.

---

[1]Arno, Stephen F. Investigation of fire history in the Bitterroot Range, ontana. (In preparation)

METHODS

Fire scars on trees were sampled intensively on three study areas in different parts of the Bitterroot National Forest (fig. 1). Each of these areas includes similar patterns of forest types extending over a broad elevational range (from about 4,000 to 8,000 feet) on a variety of exposures. The three study areas include terrain, forest types, and presumably fire histories that are representative of the 1.2-million-acre Montana portion of the Bitterroot National Forest.

Sampling and analysis techniques were developed on the Onehorse Study Area, and are explained in greater detail in Arno (footnote 1). (A "how-to-do-it" report for determining fire history based on these procedures is in preparation, by Arno and K. Sneck.) The Tolan and West Fork Study Areas were selected to provide a broader geographical basis for interpreting the role of fire in the Bitterroot National Forest. These latter sites were chosen in part because fuel-inventory studies were also being conducted there as part of the Fire in Multiple Use Management Research, Development, and Application Program (USDA Forest Service 1975). Each of the study areas was also chosen to sample unlogged forest at all elevations on a variety of aspects, and to record fire history in the form of fire scars on living trees and fire-initiated age classes of shade-intolerant conifers.

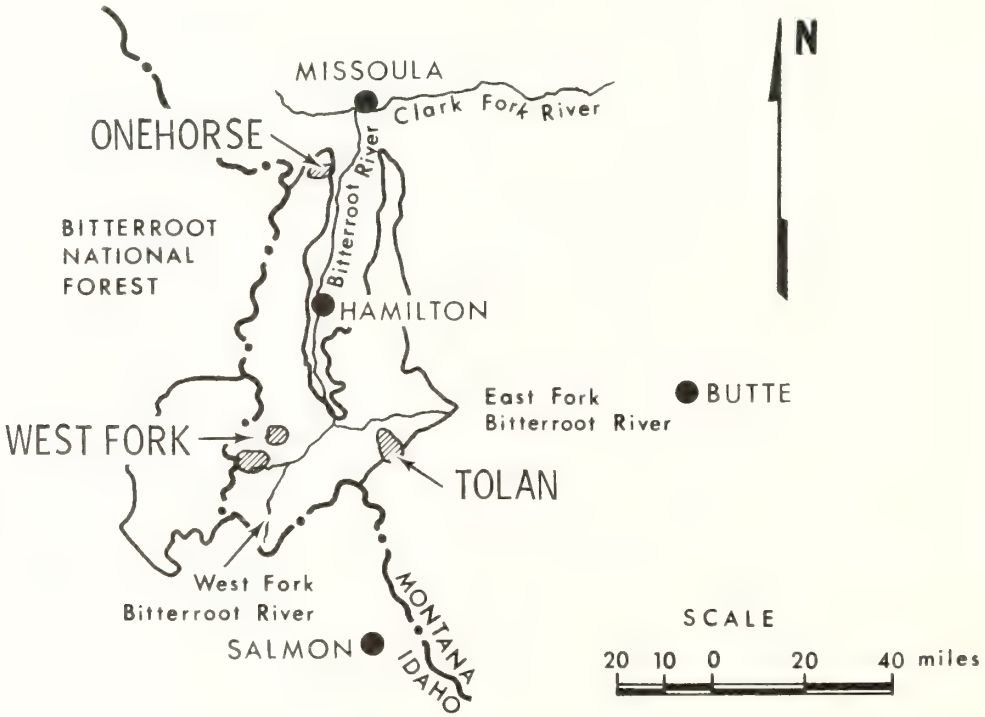

Figure 1.--Location of the three study areas.

Initially, reconnaissance transects were made along roads, trails, and cross-country routes into all major portions of each study area. An attempt was made to visit representative aspects and elevations and not to over-sample narrow, ridgeline ecotones where vegetative types and fire patterns converge. Three types of information were gathered along each transect:

1. Habitat types, identified and mapped according to the Pfister and others (in press) classification.

2. Seral stand types were described and periodically sampled, including increment boring 1 foot above ground level to identify all age classes of shade-intolerant trees. (Corings were counted in the lab.)

3. Fire-scarred sample trees, located and described in terms of number of individual scars and tree soundness (lack of decay).

After the initial reconnaissance, trees in each stand with the largest number of relatively sound fire scars were chosen for sampling. A roller-tipped chain saw was used on large trees to take a cross section of only the wood adjacent to the fire-scar wound. This "partial cross section" resulted in removal of about 10 percent of the basal area of a given large tree. Small or exceptionally rotten trees were felled. Cross sections were sanded, and rings were counted and verified with a binocular microscope (7 to 25 power) to determine the year of each fire scar.

Fire-scar sequences on individual trees were correlated with those from nearby sample trees to obtain a master fire chronology for determining actual fire years. Master chronology years should normally be within ±1 year of the actual fire except for records 250 or more years old, where accuracy diminishes. A sample of several trees is necessary to document the entire sequence of fires in one location, because individual fires often do not inflict a new wound on previously scarred trees (Arno, footnote 1).

The vertical bars in figure 2 show the number of sample trees scarred during each fire year in each of the three study areas. It is evident from the dashed line that sample size diminishes prior to the mid-1700's. This probably accounts for any "apparent" decrease in the fires prior to 1750. In contrast, despite a large sample size, fires diminished in the 1900's. Presumably, this decreasing fire occurrence partially reflects the role of organized fire suppression. Therefore, the interval 1735 to 1900 was considered to provide the best data base for analyzing fire frequencies in the era prior to fire suppression (Arno, footnote 1).

To correlate an adequate number of individual tree records for a given area, it was necessary to calculate fire frequencies for stands of 200 to 800 acres. The boundaries were drawn so that each stand represented only one category of habitat types. The fire record for each stand was thus determined by correlating the individual chronologies from the several sample trees within it. Consequently, the fire frequencies generated in this study (table 1) represent the average intervals between fires detected in a given stand. On one hand it might be argued that these intervals are actually shorter than would be expected for a given smaller stand because some of the fires detected did not cover the entire 200- to 800-acre unit. However, this effect is counterbalanced by the probability that many small or low-intensity fires were not detected in a given stand by the scarred-tree sampling. All evidence considered, these data should give a reasonable approximation of the incidence of fire in a given stand. Frequencies were averaged for all stands in a given habitat-type group in each study area. These habitat-type groups (table 1, columns 1 and 2) serve as a basis for comparison of fire frequencies within as well as among the study areas.

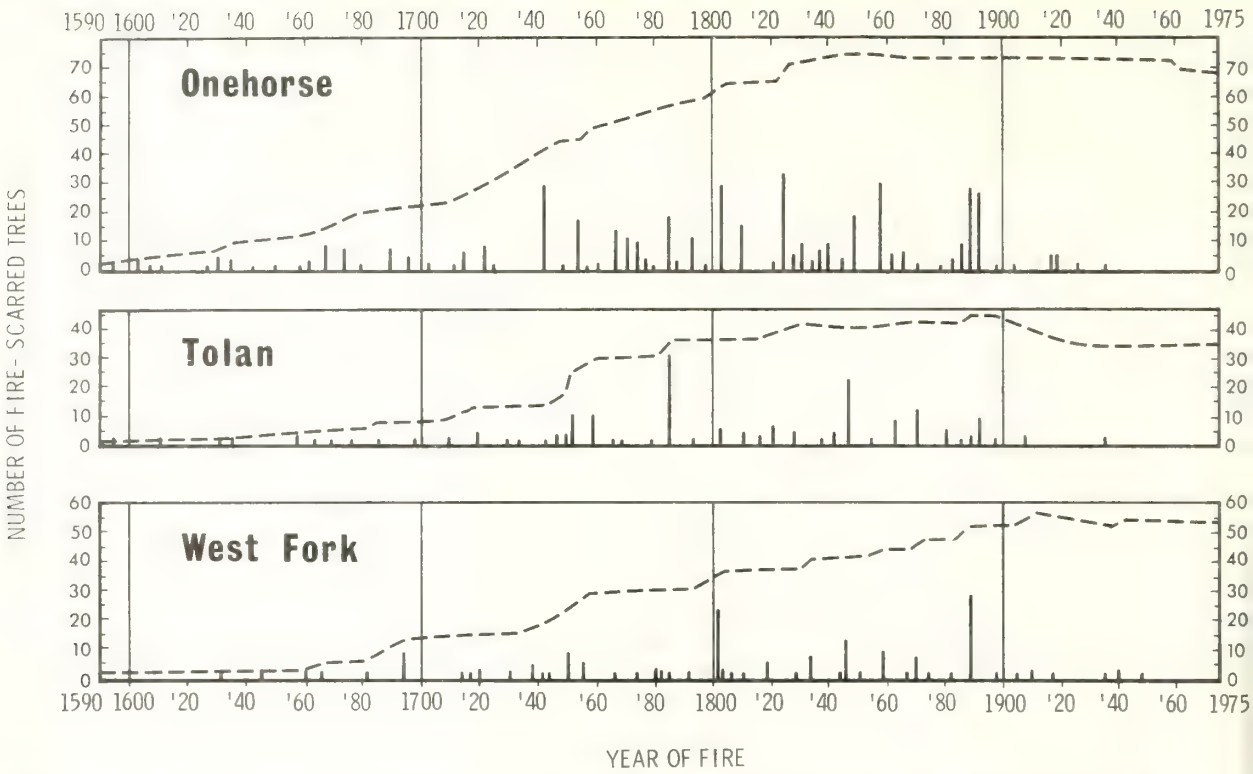
Onehorse
Tolan
West Fork
NUMBER OF FIRE-SCARRED TREES
YEAR OF FIRE
1590 1600 '20 '40 '60 '80 1700 '20 '40 '60 '80 1800 '20 '40 '60 '80 1900 '20 '40 '60 1975

Figure 2.--Forest fire chronologies for the three study areas on the Bitterroot N. F., Montana, showing the number of sample trees scarred each fire-year. Dashed lines indicate the number of fire-susceptible trees (i.e., trees already scarred at least once) in the sample.

Table 1 --Fire frequencies for the period 1735 to 1900 on the three study areas in the Bitterroot National Forest, Montana. Frequencies are based on all fire years identified within 200- to 800-acre habitat type units (stands).

Habitat type groups (potential climax) (Pfister and others, in press)	Descriptive location	General elevations (feet)	Dominant trees: with continued: fire exclusion: (most abundant: tree first)	Dominant overstory before 1900 (most abundant tree first)	Onehorse		Tolan		West Fork	
					No. of stands (No. of trees)	Mean fire-free interval (min-max interval)	No. of stands (No. of trees)	Mean fire-free interval (min-max interval)	No. of stands (No. of trees)	Mean fire-free interval (min-max interval)
1. Pinus ponderosa/Festuca idahoensis Pseudotsuga menziesii/Agropyron spicatum Pseudotsuga/Calamagrostis, P. ponderosa phase	Valley edge	3800-5000	Douglas-fir ponderosa pine	ponderosa pine	1 11)	6 years (2-20)	1 (4)	11 years (2-18)	1 (7)	10 years (2-18)
2. Pseudotsuga/Physocarpus malvaceus Pseudotsuga/Calamagrostis (except Cal. phase) Pseudotsuga/Symphoricarpos albus Pseudotsuga/Vac. globulare (except Xerophyllum phase)	Montane slopes	4200-6200	Douglas-fir	ponderosa pine Douglas-fir lodgepole pine western larch	3 (46)	7 years (2-28)	3 (11)	16 years (4-29)	4 (23)	19 years (2-48)
3. Abies grandis habitat types	Moist canyon	4300-4700	grand fir	western larch lodgepole pine Douglas-fir	1 (7)	17 years (3-32)	--	--	--	--
4. Pseudotsuga/Calamagrostis, Calamagrostis phase Pseudotsuga/Vac. globulare, Xerophyllum phase Abies lasiocarpa/Xerophyllum tenax Abies lasiocarpa/Menziesia ferruginea Abies lasiocarpa/Linnaea borealis	Lower subalpine slopes	6000-7500	subalpine fir Douglas-fir	lodgepole pine Douglas-fir	1 (9)	17 years (3-33)	3 (16)	27 years (5-62)	3 (13)	28 years (5-67)
5. Abies lasiocarpa/Luzula hitchcockii Abies lasiocarpa-Pinus albicaulis/Vac. scoparium Pinus albicaulis-Abies lasiocarpa	Upper subalpine slopes	7500-8600	subalpine fir whitebark pine	whitebark pine lodgepole pine	1 (3)	41 years (8-50)	2 (14)	30 years (4-78)	2 (14)	33 years (4-78)

RESULTS AND DISCUSSION

Data Base

A total of 889 individual fire scars (from 171 trees) were documented in the 3 study areas; 726 of these occurred in the 1735 to 1900 period. Ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), lodgepole pine (*Pinus contorta*), and whitebark pine (*Pinus albicaulis*) all had multiple fire scars dating back as far as 250 to 300 years, although in most areas the lodgepole pine fire-scar records extended back only 150 to 200 years because of stand ages. Ponderosa pine provided the clearest, most abundant, and oldest records in all study areas, with scars as old as 400 years.

The data base is displayed in tables A-1, A-2, A-3, and accompanying figures A-1, A-2, A-3 (appendix A). Table A-1 is the master fire chronology for the Onehorse area, showing the number of sample trees scarred during each fire year in each stand. Figure A-1 shows the locations of those stands and of the sample trees within them. Similarly, the paired fire chronologies and maps present the data for Tolan (table A-2 and fig. A-2) and West Fork (table A-3 and fig. A-3).

Fire Frequency

It seems apparent from tables A-1, A-2, and A-3, and especially as the total number of fire scars per study area is graphed in comparison with sample size in figure 2, that the fire frequencies remained comparably high as far back as the records go--namely, to the early 1600's at Tolan and West Fork and to about the year 1500 at Onehorse. Thus it appears that the fire frequencies during the 1735 to 1900 period represent a pattern continuing back at least to the year 1600.

A logical question that arises is how frequencies based on 200- to 800-acre stands compare with those obtained at a single point on the ground, a single tree. As an example, figure 3 shows the scarred cross section of a ponderosa pine growing on the "montane slopes" (table 1, column 2) at Onehorse. During the 1735 to 1900 period it was scarred by 15 fires at an average interval of every 11 years. This compares with an average interval of 7 years for *stands* in that category (table 1) at Onehorse. Trees growing only a few dozen yards from the one in figure 3 had scars from additional fires. It seems highly unlikely that every fire could burn hot enough at the base of any given tree in such a stand to inflict a new wound, especially when they occurred so frequently as to allow only light accumulations of fuel.

Fires occurred less often in the Tolan and West Fork areas (table 1); thus one might expect individual trees there to be exposed to more intense fires which are more likely to cause a scar. Average pre-1900 fire-free intervals were calculated for the most frequently scarred individual trees in each habitat-type group. These intervals proved to be only about 15 to 20 percent longer than those derived for the entire 200- to 800-acre stands. Even these trees might have missed being scarred in one or two fires, confirming the stand-based estimates.

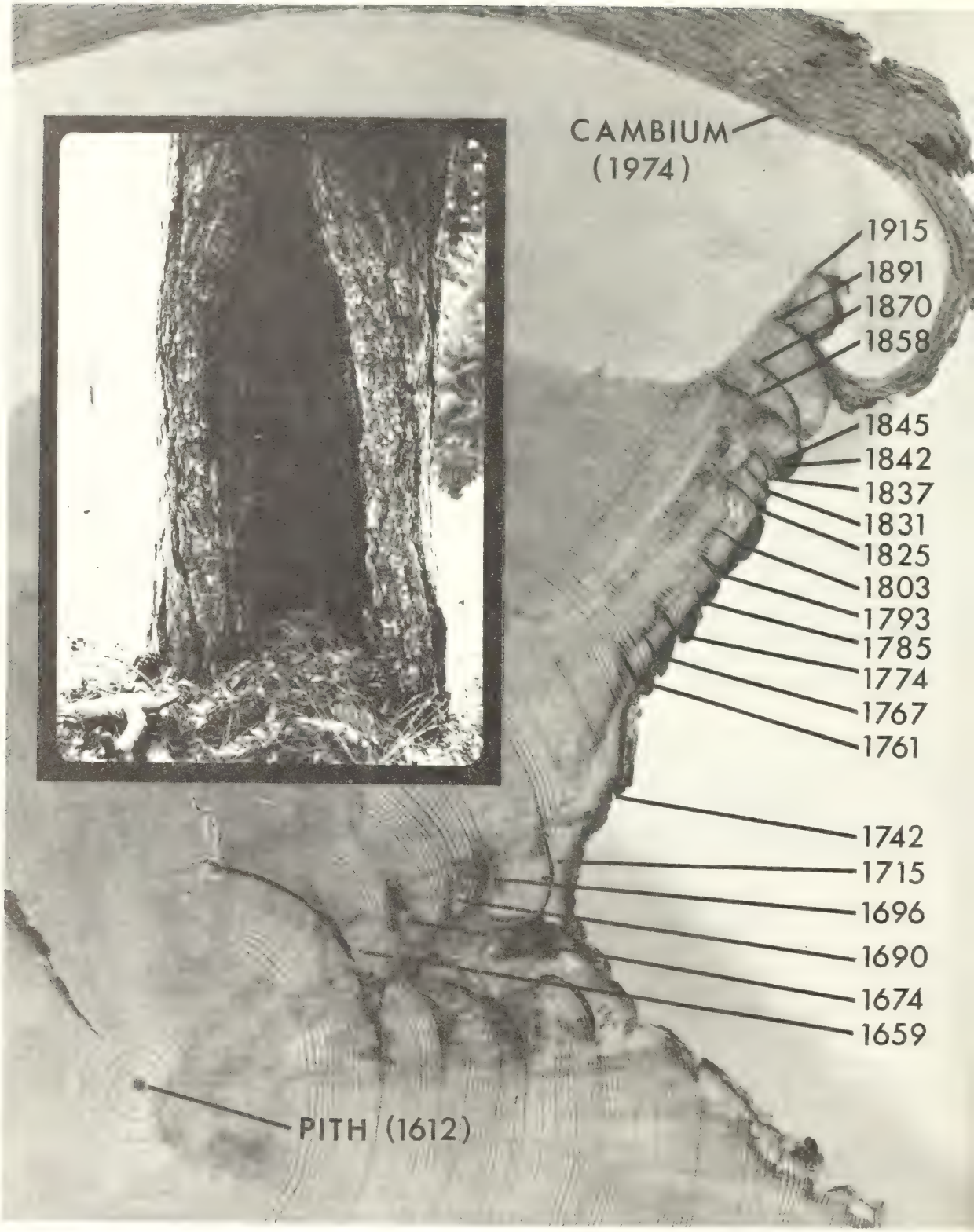

Figure 3.--Multiple fire-scar cross-section, showing 21 fire scars from 1659 through 1915. (Ponderosa pine sample tree #53, Onehorse study area, Bitterroot National Fore

These historic fire frequencies are compared in table 1 by habitat type groups for each of the three study areas. For instance, stands on the montane slopes (*Pseudotsuga/Physocarpus* and other habitat types) had average intervals of 16 and 19 years between fires in the Tolan and West Fork areas, respectively. The shortest interval detected between fires in any of the three stands in this category at Tolan was 4 years. The longest fire-free interval there, during this 1735 to 1900 period, was 29 years. During this period the dominant overstory species was ponderosa pine (table 1, column 5); whereas Douglas-fir would dominate in the absence of fire or other disturbance (column 4). Comparable interpretations can be made for other habitat types using table 1.

Inspection of table 1 reveals that the relative fire frequencies by forest categories are nearly identical at Tolan and West Fork. By contrast, fires occurred almost twice as frequently throughout the Onehorse area--except for the upper subalpine slopes where the sample size was very small, and probably inadequate. One could argue that the Onehorse area is basically drier and therefore burns more frequently, but this reasoning is not borne out by field observations or by the standardized habitat-type categories. A more plausible explanation is that fires originating on the lower slopes at Onehorse spread more readily upward throughout all the types because of the steep topography. However, the data in table 1 show that fire frequencies decrease with increasing elevation at Onehorse at a rate comparable to that of the other areas. Also, such an explanation fails to account for the high frequency of fires on the lowermost units at Onehorse.

Several threads of evidence suggest another reason for the higher fire frequency at Onehorse. Anthropologists have long recognized that Indians historically set fires in the Rocky Mountains (Malouf 1969). Direct descendants of the first settlers in the Sula Valley below Tolan study area (Marvin and William Wetzsteon at Sula, and Mr. Lord at Moosehead Museum, north of Sula, 1975, personal communication.) stated that when their grandparents homesteaded the area near the turn of the century, Indians periodically set forest fires in the nearby mountains, presumably to improve forage production for big game and horses. Indians occupied the Bitterroot Valley for at least several centuries prior to white settlement in the mid-1800's (Ward 1973). According to Dr. C. Malouf, University of Montana, Missoula (personal communication), Indians preferred the main Bitterroot Valley grasslands adjacent to the Onehorse area, therefore aboriginal burning probably would have been more common here than on the rather remote Tolan and West Fork study areas.

Still another tentative suggestion of deliberate aboriginal burning has arisen from Mehringer's (1976) analysis of 12,000 years of pollen and charcoal deposition at Lost Trail Pass Bog (located in the "lower subalpine slopes" category, table 1) 7 miles southwest of the Tolan study area. Mehringer found that airborne charcoal has been deposited continually since the reestablishment of vegetation in the area after glacial retreat 11,500 years ago. Presumably this came from fires burning in a sizable, mostly forested region upwind from Lost Trail Pass. However, the magnitude of charcoal deposition increased dramatically within the last 2,000 years despite no marked change in the forest type. To keep this idea in perspective, one must realize that to hypothesize an Indian-burning program from deposition in one bog is a large extrapolation.

Correlations Among Fire Years

Comparison of the Onehorse data with National Weather Service records between 1870 and 1920 revealed that fires were strongly correlated with drier-than-average summers (Arno, footnote 1). Table A-4 (appendix A) depicts apparent correlations

among the fire years on the three study areas. Evidently, rather extensive fires occurred simultaneously on at least two of the areas during the following years:

1892	1785
1889	1766-67
1870-71	1751-52
1862-63	1720
1858	1715
1846-47	1695-96
1828	1667-68
1802-03	1631-32

Table A-4 also shows that there were a number of years when one area was burned extensively, while the others evidently experienced little or no fire.

Extent and Severity of Fires

It is much more difficult to quantify the intensities of historic fires than it is to simply document their occurrence and determine fire frequency. Still, several sources of data can be interpreted to provide an understanding of the historic role of fire.

Implications of Fire Frequency

The relatively short intervals between fires throughout the three study areas (table 1) suggest that fire intensity was not usually great because there was little time for heavy fuel accumulation.

Age-class Findings

The r's in table A-2, for example, show that many age classes of shade-intolerant conifers were detected wherever age-class analysis was conducted (all stands except A and I). (Some of the regeneration data in table A-2 were provided by Ed Mathews, Northern Forest Fire Laboratory, Missoula, Montana.) Less intensive age-class sampling was done at Onehorse and West Fork, but nevertheless the r's in tables A-1 and A-3 show a similar pattern of multiple age classes of shade-intolerant conifers. Each age class was rather easy to relate to a fire that occurred from 3 to 10 years prior to establishment of the oldest trees in that class.

Some of the age classes detected in a stand apparently resulted from a fire that was not represented as a scar on sample trees in that stand. Fire years 1811 and 1871 in stand F (table A-2) are examples. When the adjacent stands (E and G) had both scars and regeneration dating from those fire years, it seems likely that the fire had in fact visited the stand in question (stand F).

Evidence of Fires of Various Intensities

Both field observations and table A-2 (stand D, 1821 and 1871) suggest that some fires were of such low intensity that little of the lodgepole pine overstory was killed and the stand was not opened sufficiently to allow for establishment of a new age class. This is evidence of a low-intensity, creeping ground fire in lodgepole pine stands. Similar evidence was also observed in many lodgepole forests in all but the northwestern part of Montana during field studies for the forest-habitat-type classification system (Pfister and others, in press). In northwestern Wyoming, Loope and Gruell (1973) found evidence of the historic role of creeping ground fires in lodgepole pine forests. Moreover, they stated that even under high fuel loadings recent fires have remained generall

on the ground except when encountering strong winds [illegible]. Moderate upslope winds on steep forested slopes may produce the same effect as strong winds on more gentle terrain.

In general, these interpretations for the Montana portion of the Bitterroot National Forest differ from the view presented by Wellner (1970) that fire damage was "usually extreme" in all major forest ecosystem types in the Northern Rocky Mountains except where ponderosa pine and sometimes where Douglas-fir is the potential climax. The abundance of trees with many fire scars in addition to multiple age classes over most of the landscape in the three study areas suggests that usually fire damage was not extreme.

Forests in the Montana portion of the Bitterroot National Forest are generally less productive and probably less dense than in northern Idaho where Wellner's conclusions seem most applicable. Terrain is often steep, in the Bitterroot especially on the montane slopes (*Pseudotsuga* habitat types, table 1) favoring more-intense burning. However, comparable exposures in northern Idaho, characteristically have more densely forested western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), or grand fir (*Abies grandis*) habitat types; that are evidently more likely to burn in stand-destroying fires. Large holocausts (1910, 1919, Pete King fire in 1934, Sundance and Trapper Peak fires in 1967) have occurred in northern Idaho in this century.

Most researchers are strongly tempted to generalize about fire behavior but perhaps fires in the Northern Rockies are not best described in broad generalizations. Detailed studies of fire history at various places throughout our forest types should ultimately resolve this problem.

Gabriel (1976) recently completed a detailed analysis of the fire history in some lodgepole pine-dominated forests in the Bob Marshall Wilderness of northwestern Montana. In the southern half of his study area, Gabriel documented the occurrence of low-intensity surface fires at 20- to 40-year intervals in each stand. By contrast, he found that larger, stand-destroying fires had profoundly influenced most of the northern half of his study area. However, even here he found about 20 living lodgepole pine and Douglas-fir trees having two fire scars each. This suggests a sporadic pattern of stand destruction even during relatively high intensity fires.

A small proportion of the Onehorse and Tolan areas and a sizable part of the western unit of the West Fork area were apparently burned in high-intensity fires. At Onehorse-a fire-killed stand evidently resulted from a double burn in 1889 and 1892 (Arno, footnote 1). At West Fork a sizable stand was killed in 1889. At Tolan a stand was killed at the head of the canyon bottom (between stands F, G, and H, fig. A-2) in 1785 on a site that was unique in having no evidence of fire having visited it since. In all study areas, the holocaust was restricted to areas within the lower subalpine forest dominated by lodgepole pine (*Abies lasiocarpa/Xerophyllum* and *Abies lasiocarpa/Menziesia* habitat types).

Extent of Fires

Mapping every fire that occurred in a given forest area provides insight into the extent and patterns of historic fire (Heinselman 1973). Unfortunately, such mapping, based on the fire scar and age-class data, could not be done at Onehorse because fires were too frequent. At West Fork, sampling was done in stands that were too dispersed over rugged topography to allow for mapping of individual fires. In contrast, the Tolan data was not hampered by those problems, and the age-class data was ample, thus it was possible to plot the extent of each fire detected in the Tolan drainage between 1900 and 1734 (appendix B).

Although many of these fires were not of high intensity, they were not confined to small areas. In contrast, in recent times, fires of low-to-medium intensity are

suppressed before they cover large areas, whereas high-intensity crown fires may cover large areas. Observations (Kilgore 1975; Mutch 1974) from areas where natural fires have recently been allowed to run their course (White Cap Area, Bitterroot National Forest; Grand Teton and Sequoia-Kings Canyon National Parks), show that low- to medium-intensity fires may cover large areas by advancing sporadically, often slowly, until heavy fall and winter precipitation finally extinguishes them.

Interpretations

The general pattern of fires and age classes in each stand (tables A-1, A-2, and A-3 is clearly one of frequent fires leaving substantial remnants of earlier age classes Most pre-1900 fires on the Bitterroot study areas apparently burned lightly on drier slopes at lower elevations, perpetuating ponderosa pine as the dominant species in open stands. These fires killed much of the ponderosa pine regeneration and most of the invading Douglas-fir. Fires tended to burn with greater intensity on north-facing slopes, where dense, young growth of Douglas-fir presented more opportunity for carrying a fire above the ground. Even here, however, much of the old-growth ponderosa pine, Douglas-fir, western larch, and even some lodgepole pine survived. In the lower subalpine forest, dominated by lodgepole pine, fires often were of low or medium intensity, spreading mostly on the forest floor. There were occasional hot spots where a stand was largely killed through bole heating or a "run" through the overstory.

Holocausts have also clearly been a part of the spectrum of fires (Sleeping Child, Saddle Mountain, and Corn Creek fires in 1960 and 1961) occurring on lower subalpine slopes in the Bitterroot. They are unusually intense fires that had a dramatic effect on thousands of acres of forest.

Still higher, in the upper subalpine forest, fires were least frequent and also less intense, probably because of moister and sparser fuels. Some of these latter fires undoubtedly spread upslope from more favorable burning conditions at lower elevations and then burned less intensely as fuels thinned out and moisture increased.

IMPLICATIONS FOR FIRE MANAGEMENT

Effects of Fire Exclusion

Data from all study areas (tables A-1, A-2, A-3) show a marked decrease in fire since about 1920. Modern, airborne fire-suppression techniques theoretically can result in very effective control of potentially low-to-medium intensity fires. Thus a major ecological force has been largely excluded for half a century, and the years since the last burn on most of the forested land now exceed the longest fire-free intervals recorded between 1735 and 1900 (table 1). In some forest types, this has allowed fuels to accumulate. In many stands were Douglas-fir is the potential climax tree, dense understories of this species have developed, making a ladder of fuels that now endangers even the fire-resistant, old-growth overstory of ponderosa pine, Douglas-fir, and western larch. Throughout the subalpine forest on the Bitterroot, additional heavy fuels have been generated as a result of massive overstory kills of lodgepole and whitebark pines by the mountain pine beetle (*Dendroctonus ponderosae*) in the 1920's and 1930's.

Also, severe infestations of dwarf mistletoe (*Arceuthobium* spp.) in Douglas-fir, western larch, and lodgepole pine at various locations on the Bitterroot have contributed to stand stagnation and loss of vigor. Presumably, the effect of dwarf mistletoe adds to the fuel generation rates and thus increases vulnerability of the forest to severe fire damage. This situation is partially a result of fire exclusion. Alexander and Hawksworth (1975) have analyzed current knowledge of the interrelationships between natural fire and dwarf mistletoe infestations, and have commented on possible applications of prescribed fire for control of the parasite. Other possible relationships of continued fire exclusion to insect damage, such as to western budworm in Douglas-fir and mountain pine beetle in overly dense ponderosa pine stands on the Bitterroot, also warrant concern.

Continued fire suppression without fuel management apparently promotes accumulation of fuels as well as greater continuity of fuels over the landscape; this probably favors the development of high-intensity fires.

Means for Reducing Fuels

High fuel loadings eventually will be reduced by decay, fire (wildfire or prescribe fire), or removal. Decay is relatively slow in these cool, dry forests and thus seems inadequate unless augmented by various types of prescribed fire or logging, or a combination. Where resource managers do not establish a fuel reduction program, nature may eventually do so by means of a large, uncontrollable wildfire. Mankind does not generally find this alternative safe or otherwise acceptable. Logging and slash disposa can reduce fuels in many areas. However, in some areas, this may be either uneconomical or unacceptable because of other management goals.

In the latter situation, the prescribed use of fire should be seriously considered for fuel reduction and stand management. Prescribed burning in dense stands on *Pseudotsuga* habitat types has recently been demonstrated on the Lubrecht Experimental Forest in western Montana (Norum 1976). Also, information from the following sources can supply much of the framework necessary for using fire in such stands:

1. Findings of natural fire studies in national parks (Kilgore 1975) and wilderness (Habeck and Mutch 1973; Mutch and Habeck 1975);

2. Techniques developed for managing fire in wilderness (Aldrich 1973);

3. Other current research of the Fire in Multiple Use Management Research, Development, and Application Program (USDA Forest Service 1975).

Fire could be applied when burning conditions are moderate, and are forecast to remain stable, especially in early autumn.

A burning program would require carefully developed fire prescriptions designed to accomplish management objectives, while minimizing unwanted fires (Barrows 1974). After the initial fuel reduction, maintenance of desirable fuel and stand conditions should become less difficult. A fuel management plan might incorporate both prescribed fire and naturally caused fires burning under certain conditions in specified areas. Natural fires not burning as desired would be suppressed.

Extrapolating Fire History

Resource managers should be able to approximate pre-1900 fire frequencies in variou parts of the Montana portion of the Bitterroot National Forest by extrapolating from table 1. Most areas of the Forest probably had frequencies comparable to those found at Tolan and West Fork, except that slopes of the Bitterroot and perhaps the Sapphire Range immediately adjacent to the main Bitterroot Valley may have had rates more like those at Onehorse.

The Forest habitat-type map and recent topographic maps will provide the basic information for assigning the appropriate habitat types in table 1 to the land in question. Analysis of the latest timber-inventory data and timber-type maps will be important for obtaining a knowledge of fuels and stand conditions necessary for developing fire management programs.

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APPENDIX A

Fire Frequencies and Sample Tree Locations

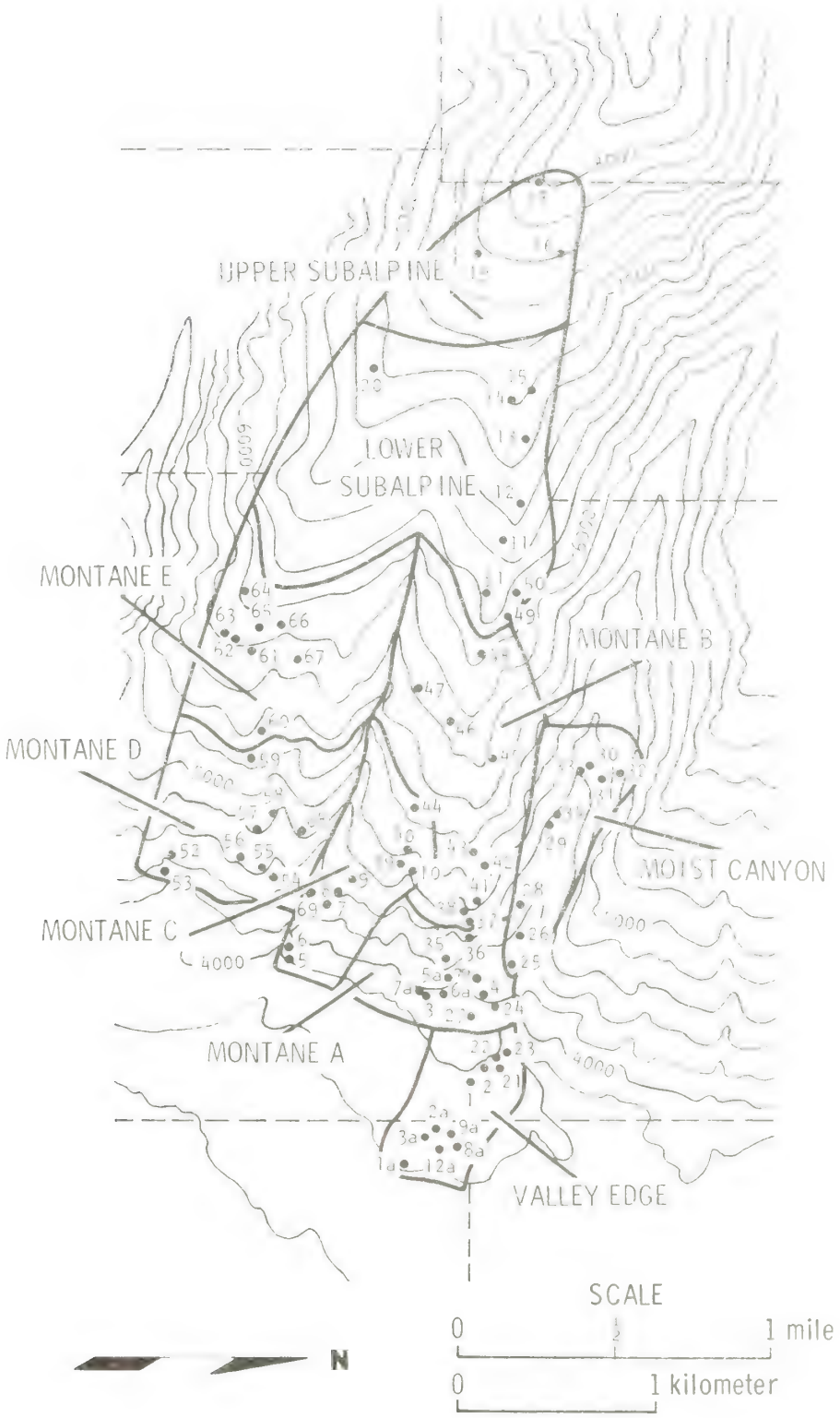
Table 2. Number of fire years and the numbers of trees scarred in each stand by 5 major habitat type units of the Beaverhead National Forest, Montana

Fire year	Habitat type groups, stands							
	1. Valley bottom	2. Montane slopes		3. Moist canyon	4. Dry lower slopes	5. Dry upper slopes		Total number of scars
	1	ABG	DGF	2	3	(3)		
1936		1						1
1926	1							1
1919		4						4
1917			4					4
1894			1					1
1889	1	10	7	3				28
1886		3						11
1883		5						5
1879				1				1
1871			3					3
1866					1			1
1862		1						6
1858**		5	11	1	3			29
1849		7	1	1				14
1845	1		4					5
1840			4		1			10
1837		1	2					8
1835	1			1				4
1831		3	2					10
1828	5							7
1825	4		12	4	2			32
1821	3							3
1810	3	6	4	1				16
1803	1	6	11	1	3			30
1800	1	5			3	1		12
1798								2
1793	4		5					12
1788		1	1					4
1785	1	4	6	1		1		19
1780	1		1					4
1777	1							
1774	1		1					11
1771				4				11
1767	2	4	1		1			15
1761			3					3
1757	1	1						2
1754	4	3	3	1	1			18
1744		1	1					2
1742	1	6	6	1	2	1		20
1725	1			1				5
1722	1	1	2		1			9
1715		1						2
1712		1	1					2
1695			1	1				4
1688	1			1				5
1680		1	1					3
1680				1		1		3
1674	1		4					9
1668	1		1					3
1662		1	1	1	1			4
1659		1		1				2
1650			1					1
1643								1
1635		1		1				4
1631		1	1	1				3
1628			1					1
1611								1
1608						1		1
1603								1
1594				1				2
1590		1	1					2
1554		1						1
1537			1					2
1531		1						1
1518		1						1
1504		1						2
1496		1		1				2
1470			1					1
1458								1
Total	133	178	131	31	24			508

* Number of sample trees.

** May include 1856 fire(s).

† Fires [illegible] conifer regeneration



sample-tree locations.

Table A-2.--Apparent fire years and the numbers of trees scarred in each stand (200- to 800-acre habitat type units) of the Tolan study area, Bitterroot National Forest, Montana.

Fire year	Habitat type groups/stands: 1. Valley edge A (4)*	2. Montane slopes B (5)	C (4)	I (2)	4. Lower subalpine slopes D (6)	D (6)	E (4)	5. Upper subalpine slopes G (6)	H (6)	Total number of scars (45)
1935	--	--	--	--	1	--	--r	--	--	1
1908	3	--	--	--	1	--	--r?	--	--	4
1898	1	--	--	--	--	--	--	--	--	1
1892	4	3r	--r	1	2r	--	--r?	--	--	10
1889	--	--	--	--	2	--	--	--	2r?	4
1886	2	--	--	--	--	--	--	--	--	2
1881	4	2	--	--	--	--	--	--	--	6
1871	3	1r?	2	2	1	3r	--r	1r	--	13
1863	3	3	1r	--	2r	--	--	--	--	9
1855	--	--	1	--	--	--	--	--	--	1
1847	3	3	2	2	5r	5r	3r	--r?	--	23
1842	4	--	--	--	--	--	--	1	--	5
1838	--	--	--	1	--	--	--	--	--	1
1828	3	--	2	--	--	--	--	--	--	5
1821	--	2r	--r	1	3	--	--r?	1r	--	7
1817	3	1	--	--	--	--	--	--	--	4
1811	--	--r	--	1	--	1r	--r	1r	2r	5
1803	4	1r?	1	--	--	--r	--r?	--	--	6
1794	--	1	1r	--	--	--	--	--	--	2
1785	3	4	--	1	3r	5r	4r	7r	4r	31
1779	1	--	--	1	--	--	--	--	--	2
1769	--	--	1	--	--	--	--	--	--	1
1766	2	--	--	--	--	--	--	--	--	2
1757	--	1	--	1	2r	1	1r	5	--r?	11
1752	--	3	--	1	1	1r	3	2	--r?	11
1750	4	--	--	--	--	--	--	--	--	4
1747	--	1	1r	--	--	1	--	1	--	4
1743	--	--	--	--	--	--	--	1	--r?	1
1734	--	--	1	--	--	1	--	--	--	2
1730	--	--	--	1?	--	--	--	--	--	1?
1720	1	2	--	--	--	--	2	--	--	5
1710	1	--	1	1	--	--	--	--	--	3
1698	--	--	--	--	1	--	--	--	--	1
1686	1	1r	--	--	--	--	--	--	--	2
1677	--	--	--	--	1	--	--	--r?	--	1
1670	--	--	--	--	--	1	--	--	--	1
1664	--	--	1	--	--	--	--	--	--	1
1658	--	--	--	1	2	--	--	--	--	3
1636	--	--	--	--	1	--	--	--	--	1
1632	--	--	--	--	--	--	--	1r?	--	1
1611	--	--	1	--	--	--	--	--	--	1
1595	--	--	--	--	--	--	--	1r?	--	1
1587	--	--	1	--	--	--	--	--	--	1
1574	--	--	1	--	--	--	--	--	--	1
Total scars	50	29	18	15	28	19	13	22	8	202

* Number of sample trees.

r Fires causing conifer regeneration based on stand age-class samples.

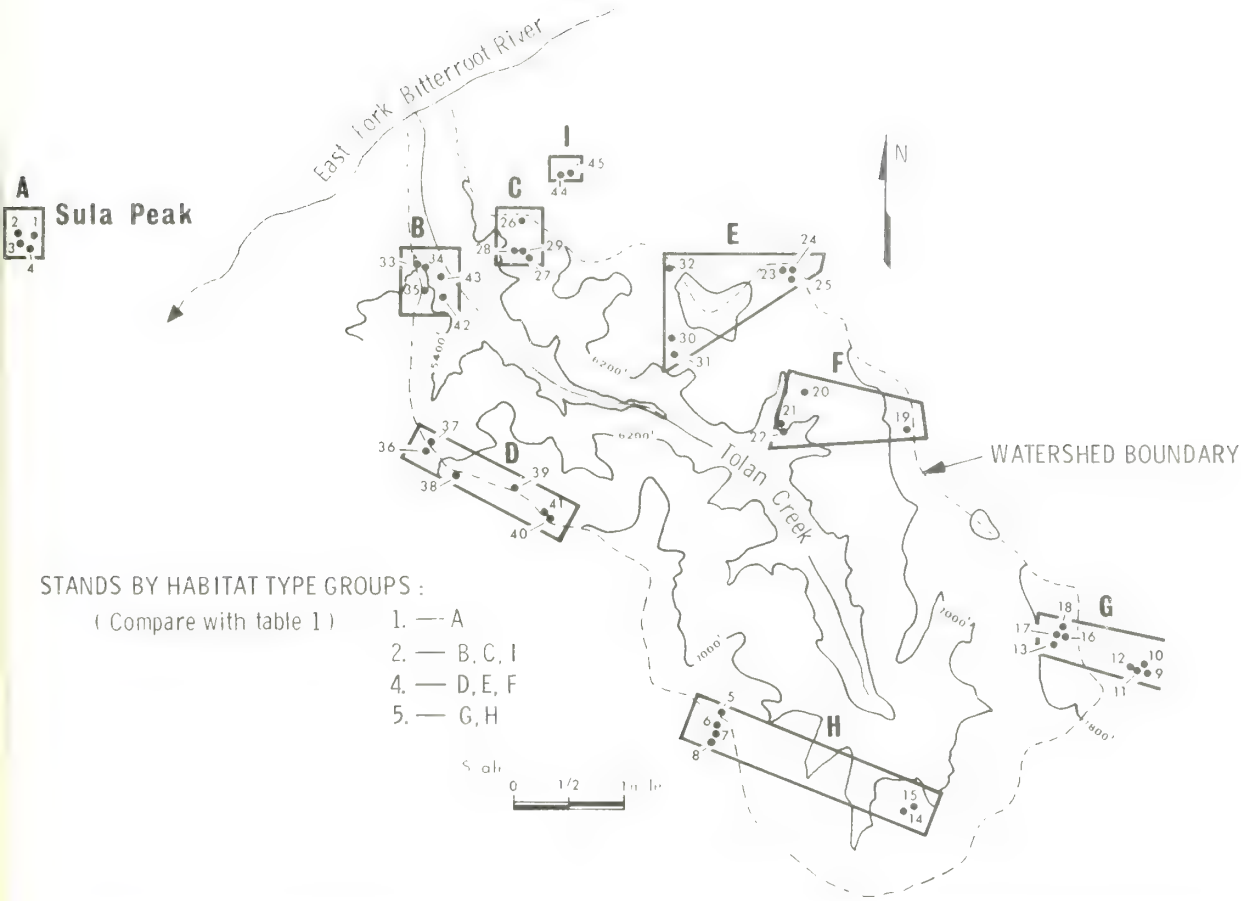


Figure A-2.--Topographic map of Tolan Creek study area (800-ft contour interval) showing sample tree locations.

Table A-3.--Apparent fire years and the numbers of trees scarred in each stand (200- to 800-acre habitat type units) of the West Fork study area, Bitterroot National Forest, Montana.

Fire-year	Habitat type groups/stands										Total number of scars (50)
	1. Valley edge	2. Montane slopes				4. Lower subalpine slopes			5. Upper subalpine slopes		
	A* (7)**	A* (7)	B (4)	C (5)	D (7)	E (4)	F (6)	G (7)	H (7)	I (3)	
1948	1	1	--	--	--	--	--	--	--	--	1
1940	--	--	--	--	--	--	3	--	--	--	3
1935	--	--	--	--	--	--	--	--	1[r]	--	1
1917	--	--	1[r]	--	--	--[r?]	--	--	--	--	1
1910	--[r]	--	--	--	--	--	1[r]	--[r?]	--	--	1
1905	--	--	1[r]	--	2	--	--	--	--	--	3
1898	--	--	--	--	--	--	--	--	1	--	1
1889	5[r]	5[r]	4[r]	3	6[r]	2[r]	4[r]	3[r]	1[r]	--[r]	28
1882	--	--	--	--	1	--	--	--	--	--	1
1875	1[r]	1[r]	--[r]	--	--	--	--	1	--	--	2
1870	--	--	--	4	--	--	--[r?]	--	2[r?]	--	6
1867	2	2	--	--	--	--	--	--	--	--	2
1859	2	2	2	--	1	1[r]	--[r?]	--	--	1	7
1851	2	2	--	--	--	--	--	--	--	--	2
1846	1[r]	1[r]	4[r]	--	6[r]	--	--	--	--	2[r]	13
1844	2	2	--	--	--	--	--	--	--	--	2
1841	--	--	--	1	--	--	--	--	--	--	1
1834	--	--	3	--	2[r]	--	1	--	2	--	8
1829	1	1	--	--	--	--[r?]	--	--	--	2[r]	3
1819	2	2	4	--	--	--	--[r]	--	--	--	6
1811	1	1	--	--	--	--	--	--	--	--	1
1807	--	--	--	--	--	1[r]	--	1[r]	--	--	2
1804	--	--	--	2	--	--	--	--	--	--	2
1802	5	5	4	--	6	2	1	3	1	1[r?]	23
1792	--	--	2[r]	--	--	--	--[r?]	--	--	--	2
1785	2	2	--	--	1	--	--	--	--	--	3
1783	--	--	--	--	2	--	--	--	--	--	2
1781	--	--	1	--	2	--	--	--	--	1	4
1774	--	--	--	--	--	--	--	--	--	1	1
1767	2	2	--	--	--	--	--	--	--	--	2
1761	--	--	--	--	--	--	--	--	--	1	1
1756	2	2	--	3	--	--	--	--	--	--	5
1751	2	2	2[r]	--	4	1	--	--	--	1	10
1744	--	--	--	--	--	--	--	1	--	--	1
1742	--	--	--	--	--	--	--	--	--	1	1
1739	2	2	1[r]	--	1	--	--	--	--[r?]	--	4
1731	--	--	--	--	1	--	--	--	--	--	1
1720	--	--	--	1	--	--	--	--	--	1	2
1718	--	--	--	--	--	--	--	--	--	--	--
1715	--	--	--[r]	--	--	--	--	--	1	1	2
1695	1	1	2[r]	--	1	1	--	--	2	1	8
1682	--	--	--	1	--	--	--	--	--	--	1
1667	--	--	--	--	--	1	--	2	--	--	3
1660	--	--	1	--	--	--	--	1	--	--	2
1646	--	--	1	--	--	--	--	--	--	--	1
1632	--	--	1	--	1	--	--	--	--	--	2
1573	--	--	--	--	1	--	--	--	--	--	1
Total scars	36	36	34	15	38	9	10	12	11	14	179

* Stand A represented both habitat type groups but is not repeated in calculating the total column.

** Number of sample trees.

[r] Fires causing conifer regeneration.

STANDS BY HABITAT TYPE GROUP

(Compare with table 1)

1. — A
2. — A, B, C, D
4. — E, F, I
5. — G, H

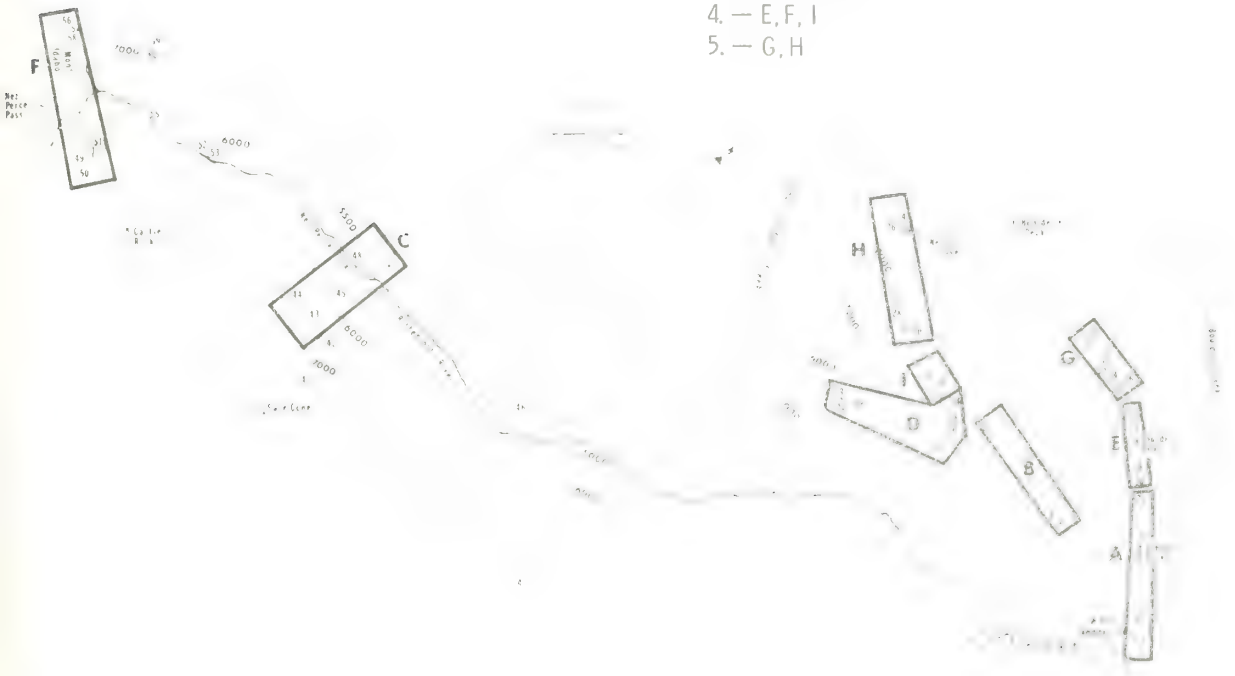


Figure 1.--A comparison of stand maps and sample tree locations.

Table A-4.--Number of sample trees scarred by year for each of three study areas on the Bitterroot National Fores
Montana. Fire-year correlations among the study areas are underlined. (n = number of sample trees)

Fire-year	n=78		n=59
[illegible]			1
[illegible]			
[illegible]		1	1
1926			
1919			
1917	4		1
1910			
1908			
[illegible]			
[illegible]			
1898			1
[illegible]	26	10	
1889	29	4	29
1886	11		
[illegible]			
1882			1
[illegible]			
1879	1		
[illegible]			2
1871	3	13	
1870			
1867			
[illegible]			
[illegible]		9	
1859			10
1858			
1855		1	
1851			
1849			
1847		23	
[illegible]			14
1845			
1844			
1842		5	
[illegible]			
[illegible]	10		
1838		1	
1837	8		
1835	4		
[illegible]			8
1831	10		
1829			3
1828	7		
1825	34		
1821			
[illegible]			
[illegible]		4	

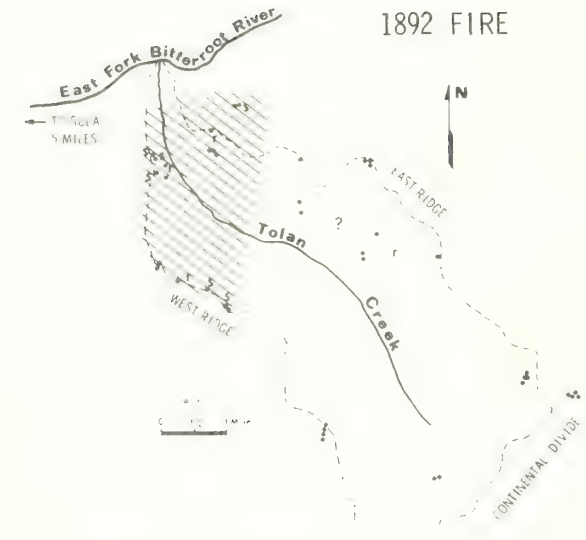
Fire-year	[illegible] n=[illegible]	Tolan n=45	West Fork n=59
1811			1
1810	1		
1807			2
1804			
1803	31	6	
1802			
1800	12		
1798	2		
1794		2	
1793	12		
1792			2
1788			
1785	15	31	3
1783			3
1781			
1780	2		
1779		2	
1777			
1774	11		1
1771	12		
1769		1	
[illegible]	15		
1766			
1761	3		1
1757		11	
1756			
1754	18		
1752		11	
1751			10
1750			
1749	2		
1747			
1744			1
1743		1	
1742	[illegible]		1
1739			
[illegible]		2	
1731			1
1730		1?	
1725	2		
1722	9		
1720		5	
1717			1
1715	7		
1712	2		
1710		3	
1703	4		
1698		1	
1696	5		
1695			9
1690	8		

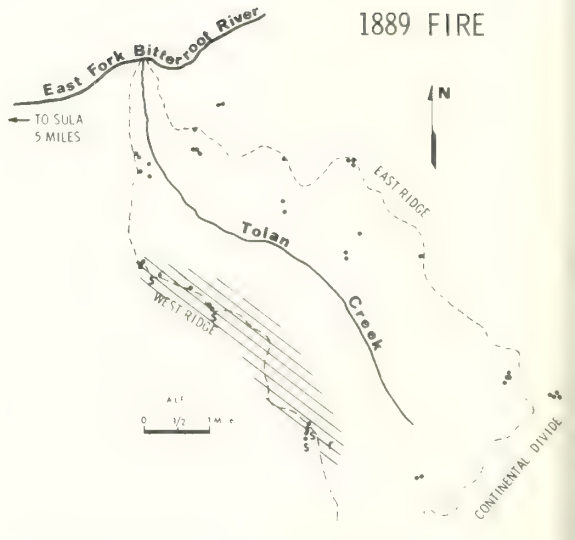
Fire-year	[illegible] n=[illegible]	Tolan n=45	West Fork n=59
[illegible]		2	
1682			1
1680	1		
1677		1	
1674	8		
1670		1	
1668			
1667			3
1664		1	
1662	3		
1660			2
1659	1		
1658		3	
1650	1		
1646			1
1643	1		
1636		1	
1635			
1632		1	2
1631			
1628	1		
1611	1?	1	
1608	1		
1603	2		
1595			
1594			
1590			
1587		1	
1574		1	
1573			1
1554	1		
1537	1		
1531	1		
1518	1		
1507	1		
1496	2		
1470	1?		
1366	1		
Totals	516	202	198

APPENDIX B

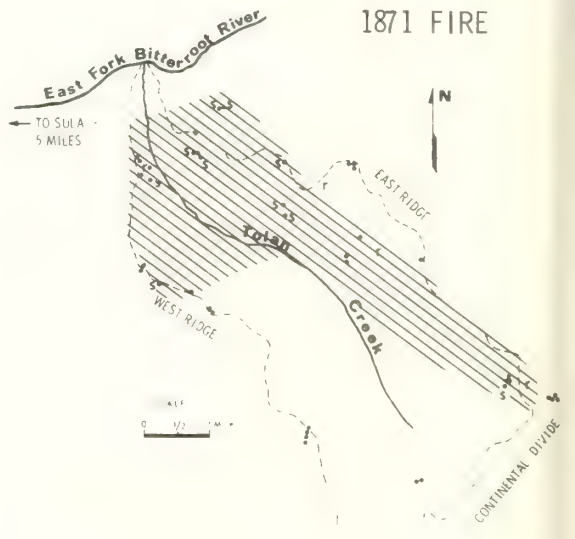
Area Covered by Individual Fires, Tolan Creek, 1900-1734

Dots show sample tree locations.
s = scar on that tree that year.
r = regeneration from that fire
detected in the stand.


1892 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE


1889 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE

1881 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE

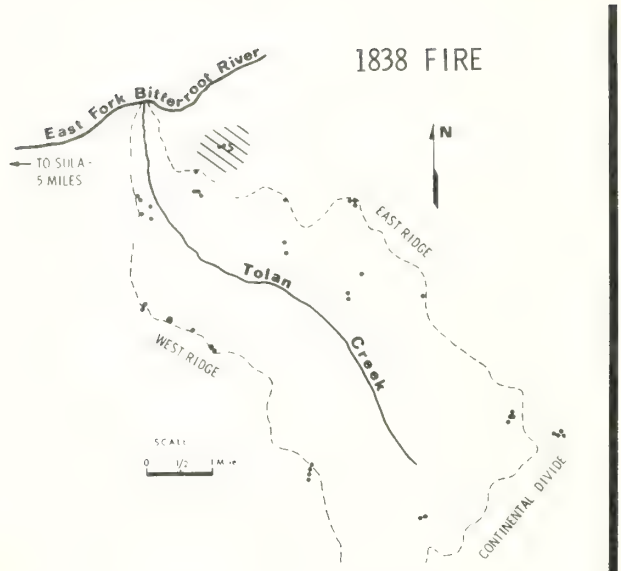

1871 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE

1863 FIRE
East Fork Bitterroot River
Tolan
Creek
N

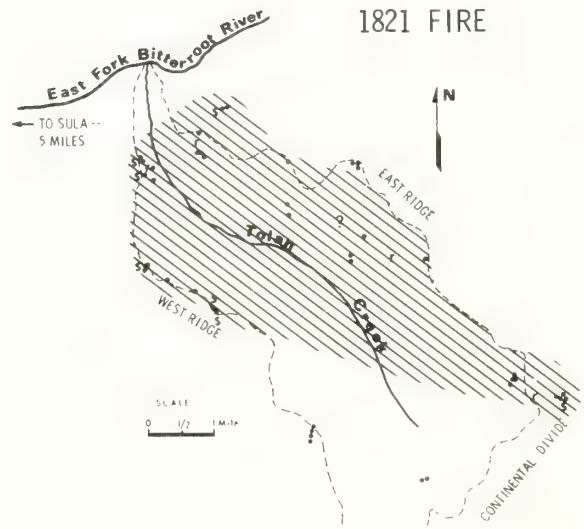
East Fork Bitterroot River
Tolan
Creek
N

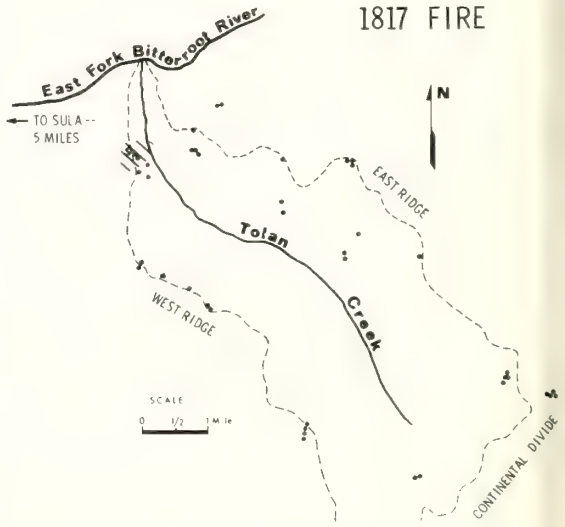
1847 FIRE
East Fork Bitterroot River
Tolan
Creek
N

East Fork Bitterroot River
Tolan
Creek
N


1838 FIRE
East Fork Bitterroot River
TO SULA -
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
SCALE
0 1/2 1 Mile
CONTINENTAL DIVIDE

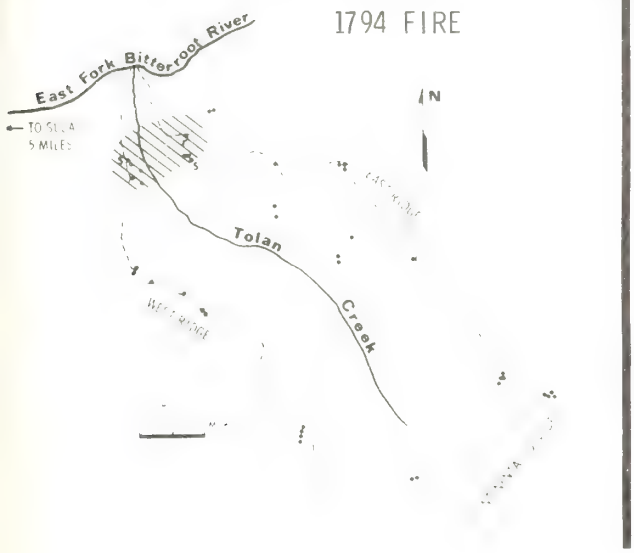
1828 FIRE
East Fork Bitterroot River
TO SULA --
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
SCALE
0 1/2 1 Mile
CONTINENTAL DIVIDE


1821 FIRE
East Fork Bitterroot River
TO SULA --
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
SCALE
0 1/2 1 Mile
CONTINENTAL DIVIDE


1817 FIRE
East Fork Bitterroot River
TO SULA --
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
SCALE
0 1/2 1 Mile
CONTINENTAL DIVIDE

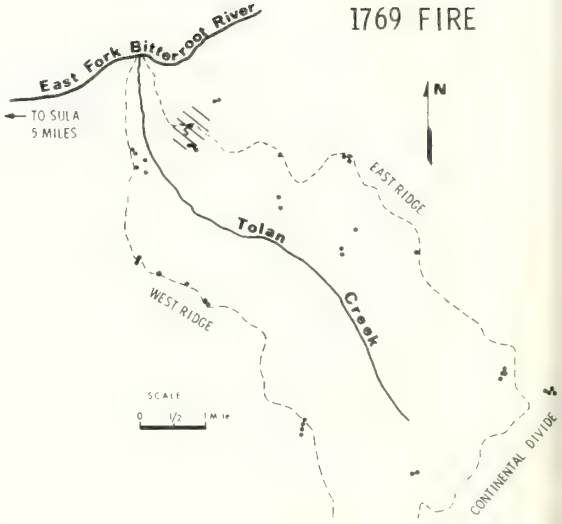
1811 FIRE
East Fork Bitterroot River
Tolan
Creek
N

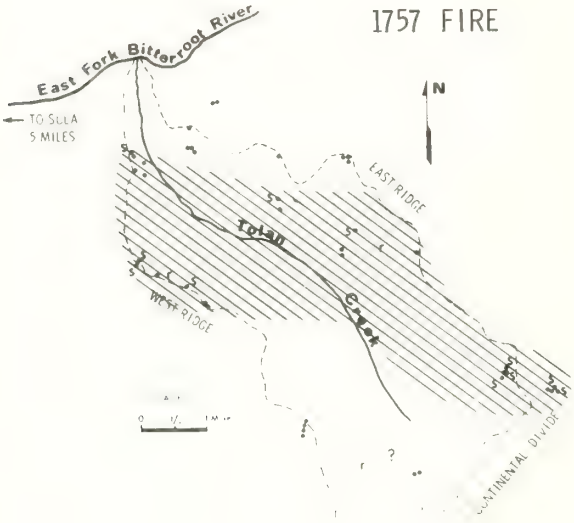
1803 FIRE
East Fork Bitterroot River
Tolan
Creek
N


1794 FIRE
East Fork Bitterroot River
Tolan
Creek
N

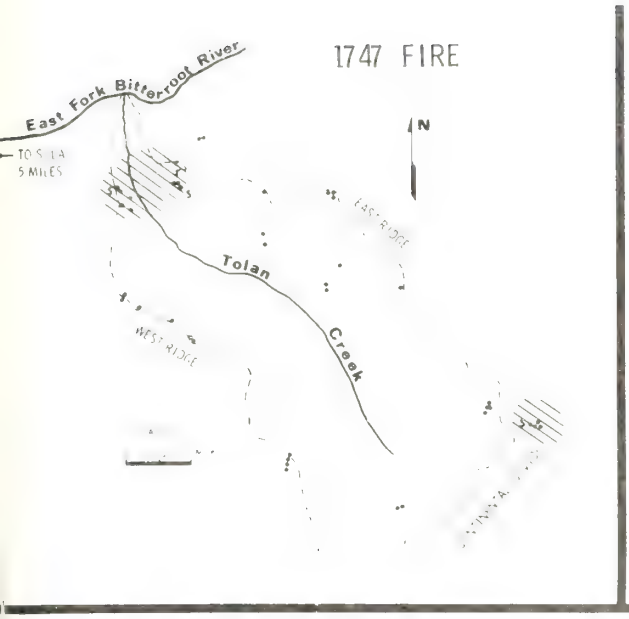
1785 FIRE
East Fork Bitterroot River
Tolan
Creek
N

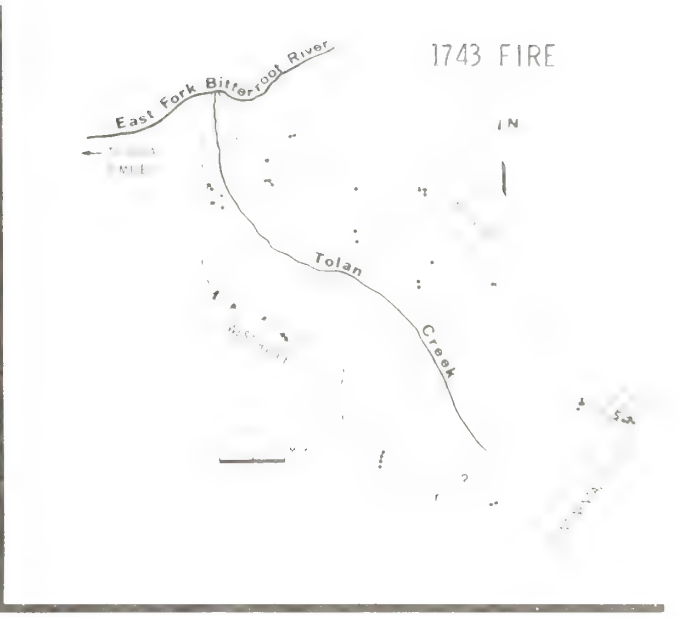
1779 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE


1769 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
SCALE
CONTINENTAL DIVIDE


1757 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE

1752 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
EAST RIDGE
Tolan
Creek
WEST RIDGE
CONTINENTAL DIVIDE


1747 FIRE
East Fork Bitterroot River
TO SULA
5 MILES
N
Tolan
Creek
WEST RIDGE
EAST RIDGE


1743 FIRE
East Fork Bitterroot River
N
Tolan
Creek

1734 FIRE
East Fork Bitterroot River
N
Tolan
Creek

Arno, Stephen F.

1976. The historical role of fire on the Bitterroot National Forest. USDA For. Serv. Res. Pap. INT-187, 29 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

Presents frequencies, intensities, and influences of fire on stand structure and composition on the Bitterroot National Forest in west-central Montana. Three study areas were established, each having a wide range of elevations and forest types. Findings are based upon study of nearly 900 individual fire scars on living trees, and on age-classes of shade-intolerant trees attributable to fire.

KEYWORDS: fire ecology, fire frequency, forest succession, habitat types.

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Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

Billings, Montana
Boise, Idaho
Bozeman, Montana (in cooperation with Montana State University)
Logan, Utah (in cooperation with Utah State University)
Missoula, Montana (in cooperation with University of Montana)
Moscow, Idaho (in cooperation with the University of Idaho)
Provo, Utah (in cooperation with Brigham Young University)
Reno, Nevada (in cooperation with the University of Nevada)

RESPONSE OF BLUE HUCKLEBERRY TO PRESCRIBED FIRES IN A WESTERN MONTANA LARCH-FIR FOREST

Melanie Miller

USDA Forest Service
Research Paper INT-188
INTERMOUNTAIN FOREST AND
RANGE EXPERIMENT STATION

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Melanie Miller

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

RESEARCH SUMMARY

In a western larch/Douglas-fir forest type in western Montana, 9 spring and 11 fall understory burns were conducted. Multiple regression equations related the number of Vaccinium globulare (blue huckleberry) stems present 1 and 2 years after fire to the number present before fire, prefire fuel loadings, moisture content of fuel, duff and soil, environmental conditions, fuel reduction, fire intensity, and temperatures reached at duff and soil surfaces during the fires. Postfire Vaccinium numbers were most closely related to the number of Vaccinium present before fire. The number of sprouts depended upon the fire treatment received by stems and rhizomes. There was no evidence of any seasonal variation in the physiological ability of Vaccinium to produce sprouts.

In the spring, mostly fine fuels burned; in the fall, dry large fuels and duff layers often burned. All spring fires increased Vaccinium stem numbers. Plants were pruned but high duff and soil moisture protected rhizomes from heat. Many more rhizomes were killed during fall fires than spring fires. Soil moisture was too low to protect rhizomes from the great amounts of heat released.

INTRODUCTION

Many species of shrubs common to western forests respond to fire by reproducing egetatively. After fire has killed the top of the plant, sprouts develop from root rowns or from rhizomes, underground stems located in duff and soil layers (fig. 1).

Vegetatively reproducing shrubs are among the first species to recolonize an area fter fire. New growth provides forage and often bears increased fruit crops. Cover s provided for small wildlife species. Lush vegetation can protect the soil surface rom splash erosion, but can also offer severe competition to new tree seedlings. An nterlacing network of *Vaccinium* rhizomes and roots can be very effective in preventing ater and wind erosion on slopes (O'Rourke 1942), a function that would be particularly mportant on a site where aboveground vegetation had been temporarily removed by fire. ecause rhizomes store and translocate nutrients absorbed by their adventitious roots Trevett 1956b), a living rhizome system can be very important in retaining nutrients eleased by fire.

Vaccinium globulare (blue huckleberry), *V. membranaceum* (mountain huckleberry) Minore 1975), *Symphoricarpos albus* (snowberry), and *Spiraea betulifolia* (white spiraea) prout after fire from dormant buds located on rhizomes. The amount of shrub sprouting ay vary widely after fires in different locations or seasons, and within the area of single fire. Specific factors that account for these differences have not been iden- ified.

An increased use of prescribed fire is being considered by forest managers to re- uce understory fuels, thin stands, and manipulate wildlife habitat. Managers must xecute burns under specified burning conditions to achieve desired objectives. We ave not known whether a specific relationship exists among burning conditions, fire haracteristics, and shrub response. The important role that shrubs play in determining ostfire site quality demands that they be taken into account when planning prescribed urning.

igure 1.--Rhizome section of Vaccinium globulare. *Arrows indicate location of several dormant buds.*

Background

A study was developed at the Northern Forest Fire Laboratory of the USDA Forest Service to obtain criteria for scheduling prescribed fires to obtain desired levels of understory fuels (Norum 1975). Twenty understory burns were conducted in Douglas-fir/western larch stands from May 11 to June 29, and September 11 to October 11, 1973. Plots averaged one-third acre. Strip headfires were ignited at 5-meter intervals with drip torches.

Fuels were sampled before and after fire. Downed woody fuels were inventoried by the planar intersect method (Brown 1975). Herbaceous biomass and duff depth were measured. Shrub stems were counted to predict shrub biomass (Brown 1976). Moisture content as a percent of ovendry weight was determined for samples of fuel, duff, and the top 5 cm of soil collected just before plot ignition. Asbestos plates with stripes of temperature-sensitive paint monitored duff and soil heating to depths of 15 cm (5.9 inches). Fuel loadings, fuel and duff moisture contents, and environmental parameters were statistically related to fuel reduction, fire intensity, soil temperatures attained during burning, small-stem mortality, and percentage of cambial kill of trees greater than 5 inches d.b.h. (Norum 1975).

Objectives

A study was undertaken to determine whether fuel loading, burning conditions, or fire effects could be related to differences in shrub response (Miller 1976). This report is based upon that study.

Study objectives, as modified, were to:

1. Relate the number of *Vaccinium globulare* stems on the burn plots 1 and 2 year after fire to:

    a. Preburn conditions

        - fuel loading
        - number of *Vaccinium* stems

    b. Season of burn

    c. Burning conditions

        - atmospheric conditions
        - dead woody fuel moisture
        - duff and soil moisture

    d. Fire effects

        - fuel reduction
        - fire intensity
        - duff and soil heating

2. Identify factors that promoted or inhibited *Vaccinium* sprouting. If firm relationships were established, formulate guidelines for *Vaccinium* management by means of understory burning.

LITERATURE REVIEW

Heat Transfer in Soil

Wijk (1963, in Smith 1966b) has stated that heat is transferred through soil largely by conduction. Wet soil is a better conductor of heat than dry soil. However, wet soil is heated more slowly than dry soil because water requires more heat energy than a solid to raise its temperature an equivalent amount.

Albini (personal communication 1975, Northern Forest Fire Laboratory) has said that the principal method of heat transfer through a porous medium such as duff or soil is vapor transfer. Water in duff layers is evaporated by fire, absorbing about 540 cal/g of heat in the process. The vapor moves in all directions in response to the vapor pressure gradient. Some steam will move downward through the profile in macropore spaces, condensing on cool surfaces if the relative humidity is near 100 percent. The latent heat absorbed during evaporation will be released as vapor condenses. If duff and soil are dry, heat will be directly transferred to the particles. If water is present, the latent heat will be expended in heating the water. Only a very small amount of heat would be transmitted to duff and soil particles with a film of water above them. Uggla (1973) has described a "sweating zone" immediately below the fire surface in thick moist humus, the result of condensation of fire evaporated moisture on the cold humus surface.

According to Albini (personal communication 1975, Northern Forest Fire Laboratory), this layer will insulate layers below from further heat penetration until it is completely evaporated by fire heat. Moist soil layers may also retard heat penetration by deflecting additional steam back toward the surface. The amount of deflection may be related to the amount of water in soil macropore space. Duff and soil moisture are thus important regulators of heat penetration into the forest floor.

Shearer (1975) found that root mortality in nonconiferous species resulting from slash burns in Douglas-fir/western larch varied according to the interaction between fire heat and soil water. Maximum soil temperatures occurred on microsites with high fuel concentrations, low soil moisture, or both. When soil moisture content averaged 20 percent and moisture content of lower duff averaged 28 percent, considerable soil heating resulted from fires of even low intensity.

Vaccinium Response to Fire

Individual clones of *Vaccinium* have an extensive rhizome system, only a small part of which is manifested by aboveground shoots (Smith 1966a). Rhizomes of *V. angustifolium* are concentrated in the organic and surface soil layers (Trevett 1956b), while *V. membranaceum* rhizomes are generally found between 8 and 30 cm below the surface (Minore 1975). *V. globulare* rhizomes are most densely distributed in the top 10 to 15 cm of duff and soil, but have been found at depths of 25 cm below the duff surface (personal observation). Dormant buds are evenly distributed across all rhizome surfaces of these species, although they are sometimes deeply buried in tissue on thicker rhizomes.

Fields of *V. angustifolium* in eastern Canada and the northeast United States are pruned with fire to increase commercial blueberry production. Burns are conducted in fall or spring when plants are dormant and wet ground protects the rhizomes from fire (Badcock 1958). Straw is often used to carry fire. Fires need not be intense since plant tissue is killed by temperatures of 50° to 60° C (122° to 140° F) (Meyer and others 1973).

The stand thickens in response to fire pruning by producing new sprouts from the dormant buds at the base of burned stubs or from rhizomes just below the ground surface (Trevett 1956a). The buds that elongate are those few closest to where the stem or rhizome is killed. Whether pruned in the fall or in early spring, shoots emerge in May (Eaton and White 1960). Energy for growth comes from carbohydrate stored in rhizomes and roots. Stained rhizomes of *V. globulare* collected in early June and early July had abundant starch grains, except for an apparently young rhizome of small diameter that had no starch grains (personal observation).

New rhizomes are often produced in response to vigorous aerial plant growth (Kender 1967). Rhizomes initiated from buds at deep levels tend to "migrate" laterally, becoming important in extension of clonal boundaries (Trevett 1956b). Rhizomes initiated from buds near the surface tend to turn toward the surface and produce leafy shoots after emerging from the ground. The shoot tips may be stimulated to grow toward the surface by very small amounts of light, because low-intensity light has induced laterally growing rhizomes to become vegetative shoots in laboratory experiments (Barker and Collins 1963). Trevett (1956b) postulated that duff reduction by fire could result in stem development from rhizomes which had been growing laterally. This could occur if duff thinning allowed light to penetrate to rhizome tips.

The *Vaccinium* plants on a site after a fire are mixtures of unburned plants and newly regenerated plants. Seedlings of *Vaccinium* are rarely found and are not important in recolonization of burned sites after fire (Peter Stickney, personal communication 1976, Forestry Sciences Laboratory, Missoula, Montana). Some new stems may result from rhizome growth stimulated by fire. Most of the newly regenerated plants are sprouts induced by fire killing of stems and rhizomes. The postfire stand of *Vaccinium* is thus closely related to the fire treatment that plants receive.

STUDY AREA AND TREATMENT

The study area was within the University of Montana Lubrecht Experimental Forest northeast of Missoula, Montana, at an elevation of 1,460 meters (4,800 feet) m.s.l. Plots were on northwest to northeast aspects on slopes ranging from 15 to 45 percent. The sandy textured soils of the Holloway Series are thin and poorly developed with numerous quartzite argillite rocks of varying sizes (Stark 1976). The dead and down woody fuel loading on the fire plots ranged from 1.4 to 11.4 kg/m^2 (6 to 51 tons per acre). Very old partially decomposed slash from light selective harvests prior to 1930 was supplemented by considerable amounts of naturally accruing fuels (fig. 2 and 3).

Figure 2.--Fuels typical of Lubrecht Forest.

Figure 3.--Logging slash from selective cutting.

Habitat types were classified according to Forest Habitat Types of Montana (Pfiste and others, review draft, 1974. Forestry Sciences Laboratory, Missoula, Montana). The area is predominantly in the *Pseudotsuga menziesii-Vaccinium globulare* habitat type, *Arctostaphylos uva-ursi* phase, with certain plots transitional to the *Pseudotsuga menziesii-Xerophyllum tenax* habitat type, *Arctostaphylos uva-ursi* phase. The overstory is a fully stocked stand of all-aged Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (taxonomic nomenclature for Lubrecht species follows Hitchcock and Cronquist 1973), western larch (*Larix occidentalis* Nutt.), lodgepole pine (*Pinus contorta* Dougl.), and an occasional ponderosa pine (*Pinus ponderosa* Laws.). The undisturbed shrub understory is dominated by blue huckleberry (*Vaccinium globulare* Rydb.) or white spiraea (*Spiraea betlifolia* Pall. var. *lucida* Dougl.), or both; or blue huckleberry and menziesia (*Menziesi ferruginea* Smith), with occasional snowberry (*Symphoricarpos albus* (L.) Blake), willow (*Salix scouleriana* Barratt), rose (*Rosa* spp.), and serviceberry (*Amelanchier alnifolia* Nutt.) (fig. 4 and 5).

The number of *Vaccinium* stems, fuel loading, and atmospheric conditions were similar between spring and fall burned plots at the time of their ignition. Fuel, duff soil, and understory foliage moisture content varied considerably between the two burning seasons. Measured fuel, duff, soil, and foliar moisture content are indicated in figure 6. Figure 7 shows a theoretical curve for large fuel moisture content based upon an analysis by Brackebusch (1975).

Figure 4.--Most forest openings contained dense stands of Vaccinium globulare.

Figure 5.--Typical Vaccinium*--fuel association.*

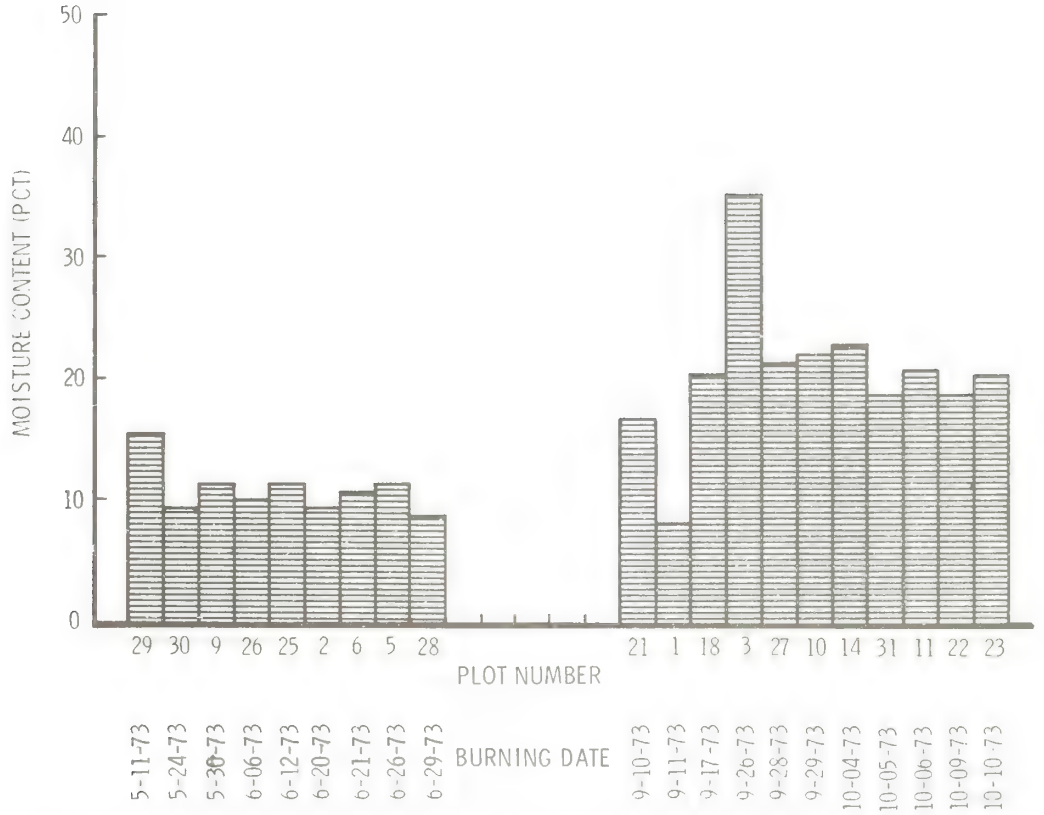


Figure 6a.--0 to 0.635 cm (0 to 1/4 inch) diameter fuel moisture content.

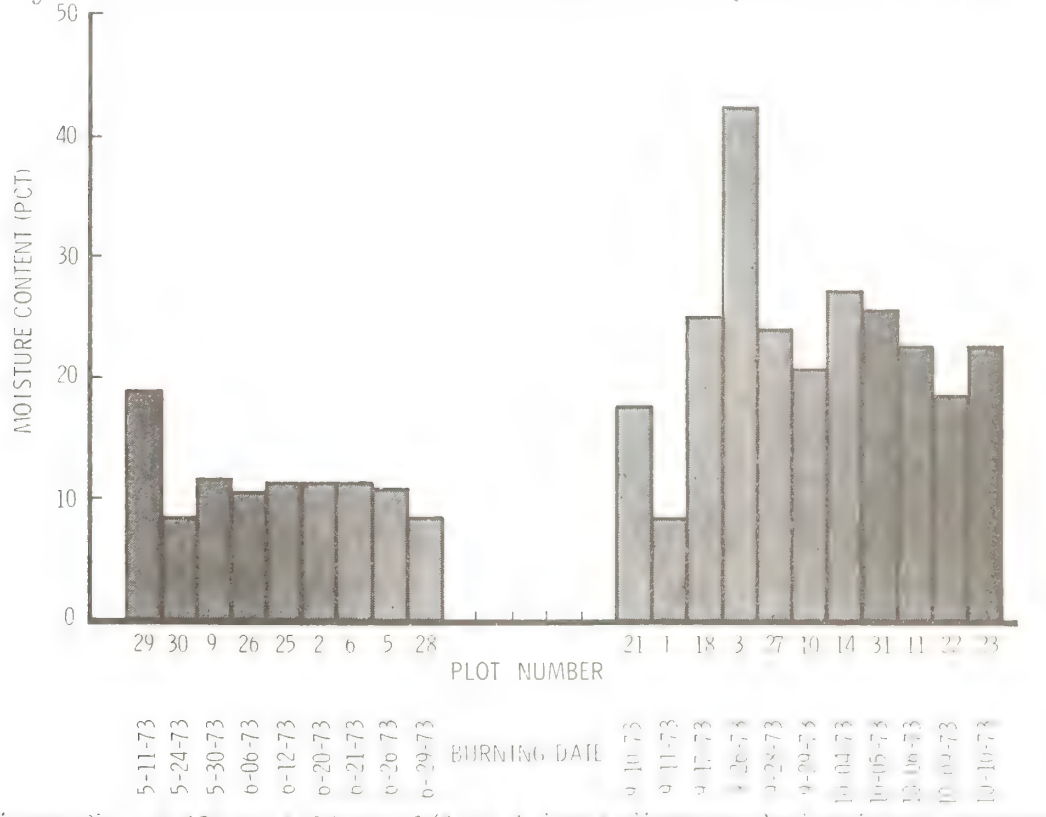


Figure 6b.--0.635 to 1.54 cm (1/4 to 1 inch) diameter fuel moisture content.

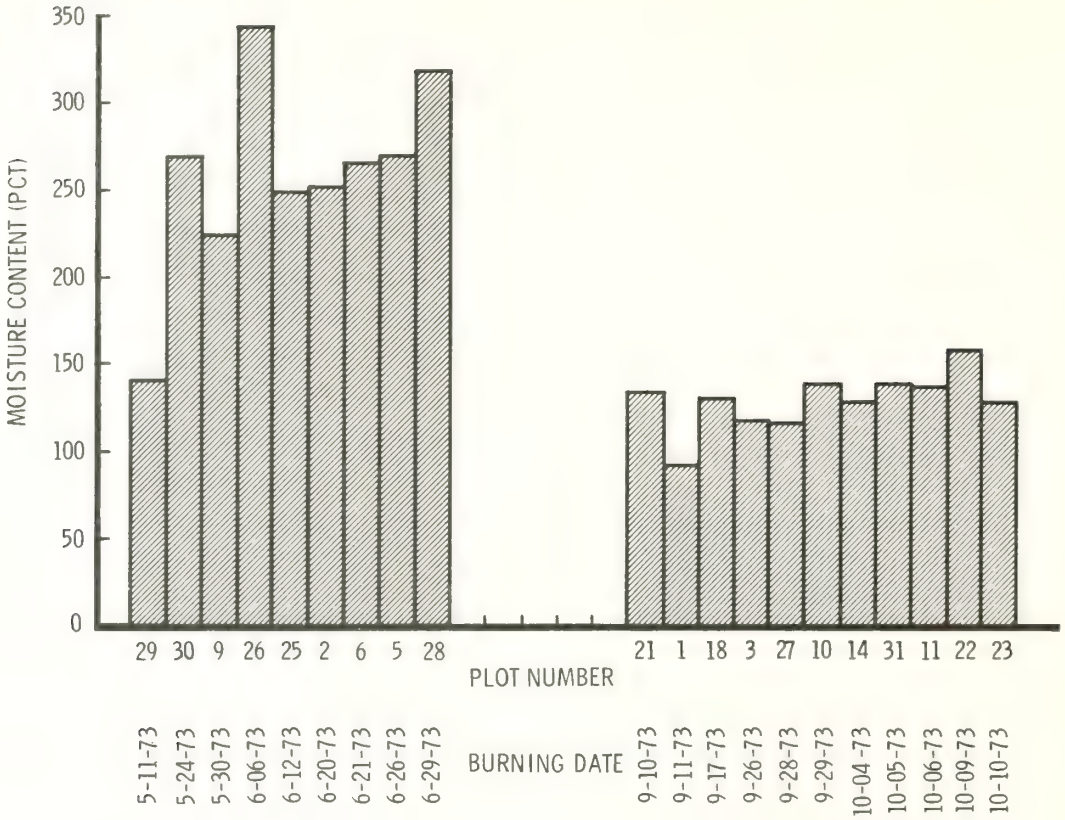


Figure 6c.--Understory foliage moisture content (percentage).

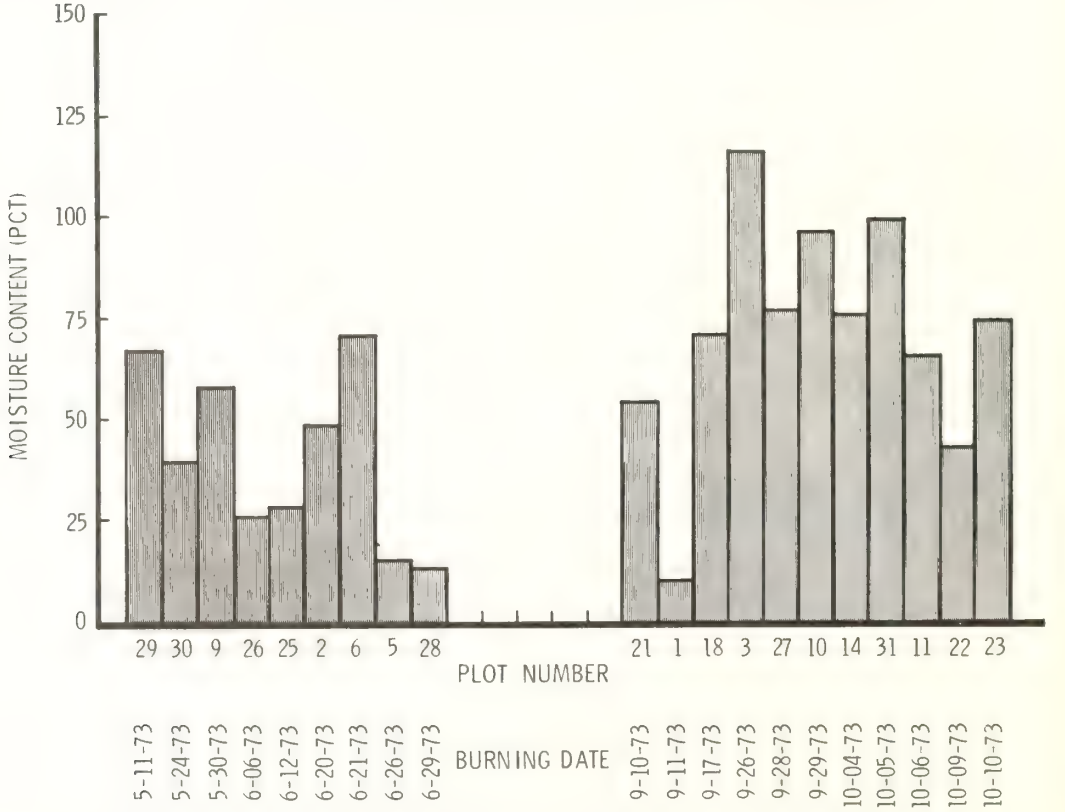
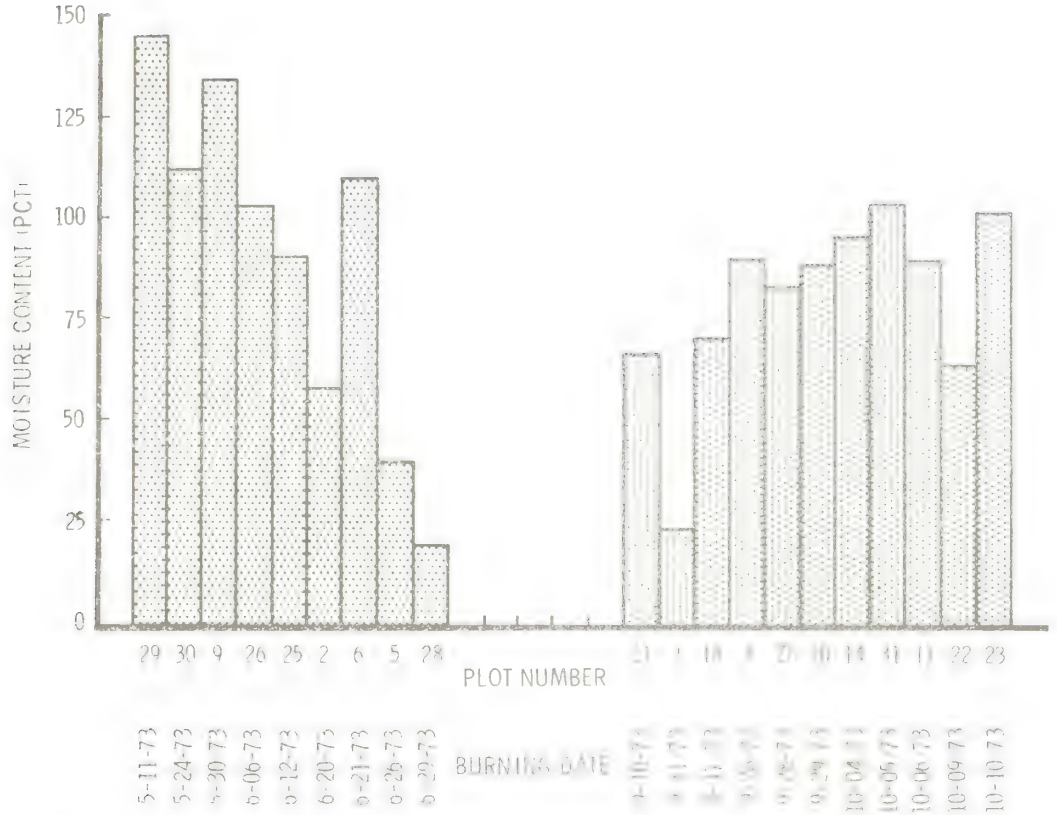
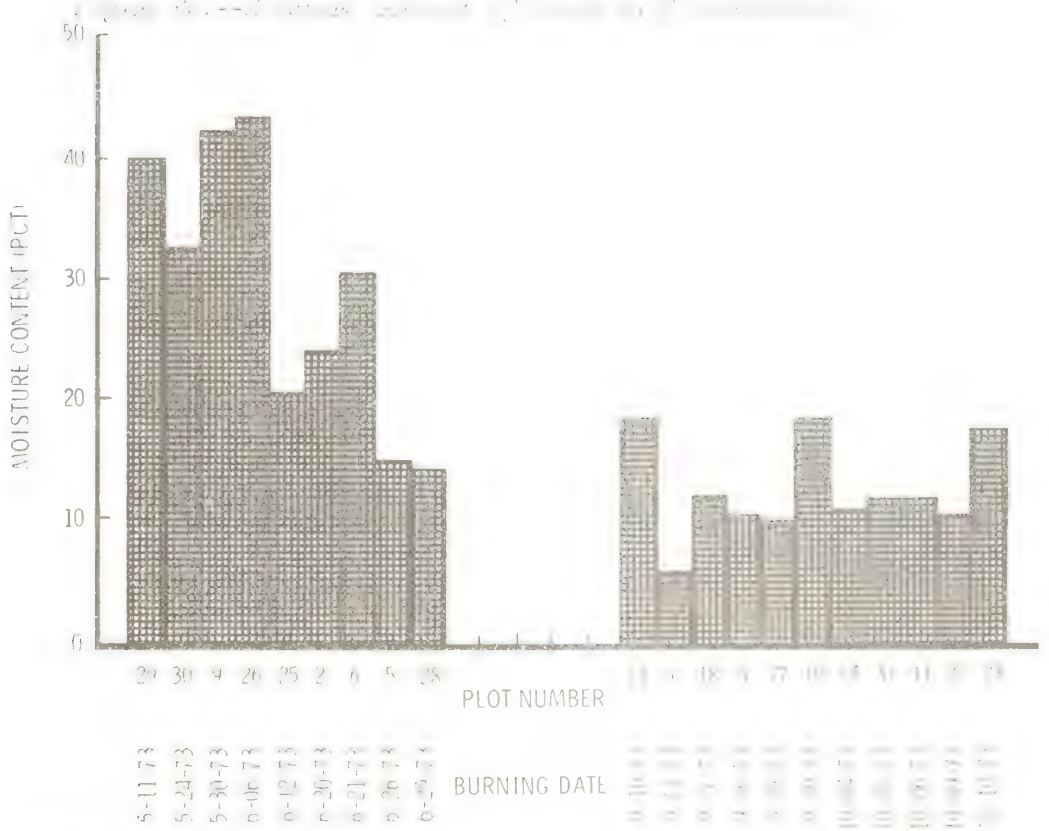


Figure 6d.--Moisture content of upper duff (percentage).


150
125
100
75
50
25
0
MOISTURE CONTENT (PCT)
29 30 9 26 25 2 6 5 28
PLOT NUMBER
5-11-73
5-24-73
5-30-73
6-06-73
6-12-73
6-20-73
6-21-73
6-26-73
6-29-73
BURNING DATE


50
40
30
20
10
0
MOISTURE CONTENT (PCT)
PLOT NUMBER
BURNING DATE

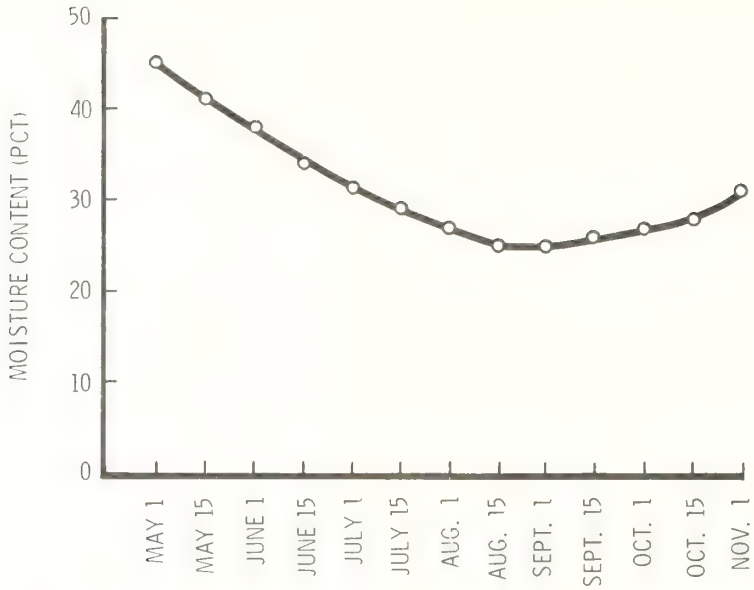


Figure 7.--Moisture content of large sound fuels (percentage).

Moisture content of understory foliage was high in the spring because of the flush of new growth. Fuel, duff, and soil moisture decreased throughout the spring. Fall rains raised the moisture content of fine fuels and duff but apparently did not soak through to soil layers. Large fuels were still dry in the fall season (Rodney A. Norum personal communication, 1976, Northern Forest Fire Laboratory).

Fire effects varied between seasons. Spring fires were more intense in terms of maximum energy output per unit time, as calculated according to Van Wagner's formula relating fire intensity to crown scorch height (Norum 1975). However, fall fires produced larger amounts of total heat, caused greater duff and soil heating, and led to more complete combustion of fuels and duff than occurred in the earlier burning season.

Duff drying and consumption were promoted by the burning of associated fuels (Norum 1975). Burning duff contributed to heating of adjacent duff and soil layers. (Frank A. Albini, personal communication 1976, Northern Forest Fire Laboratory). Duff depth reduction and average mineral soil surface temperature, indicated for each plot in figure 8, describe the differences in the subsurface heat regime.

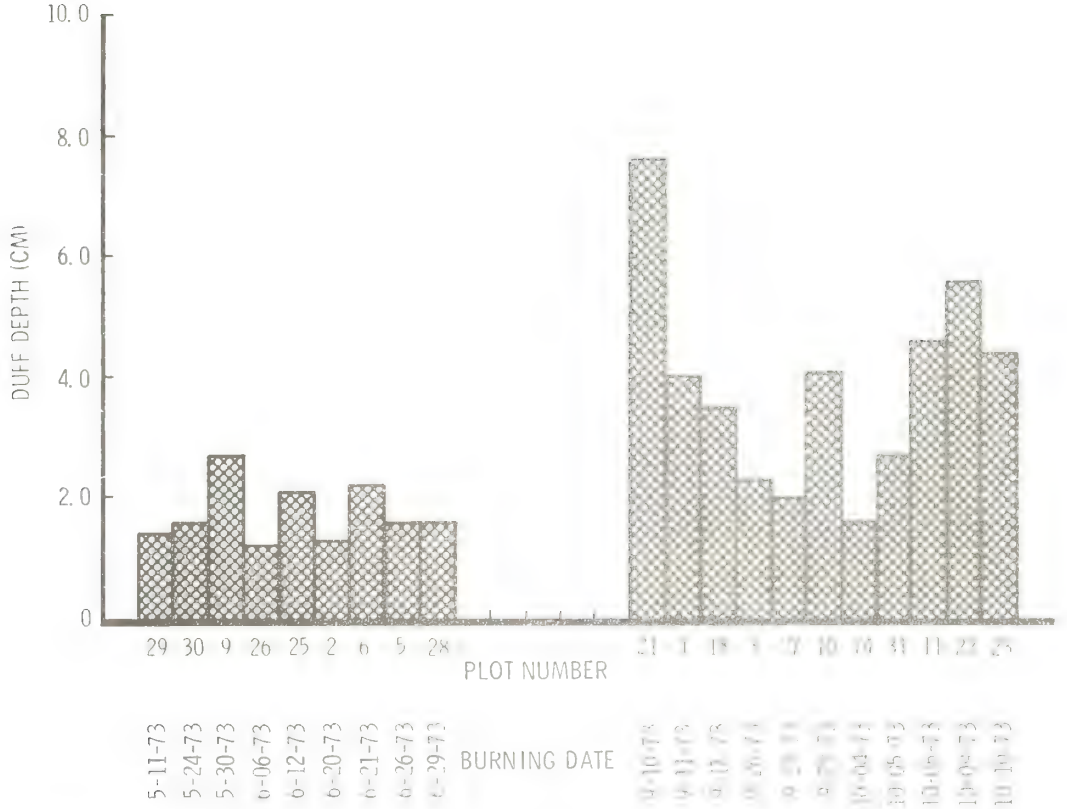
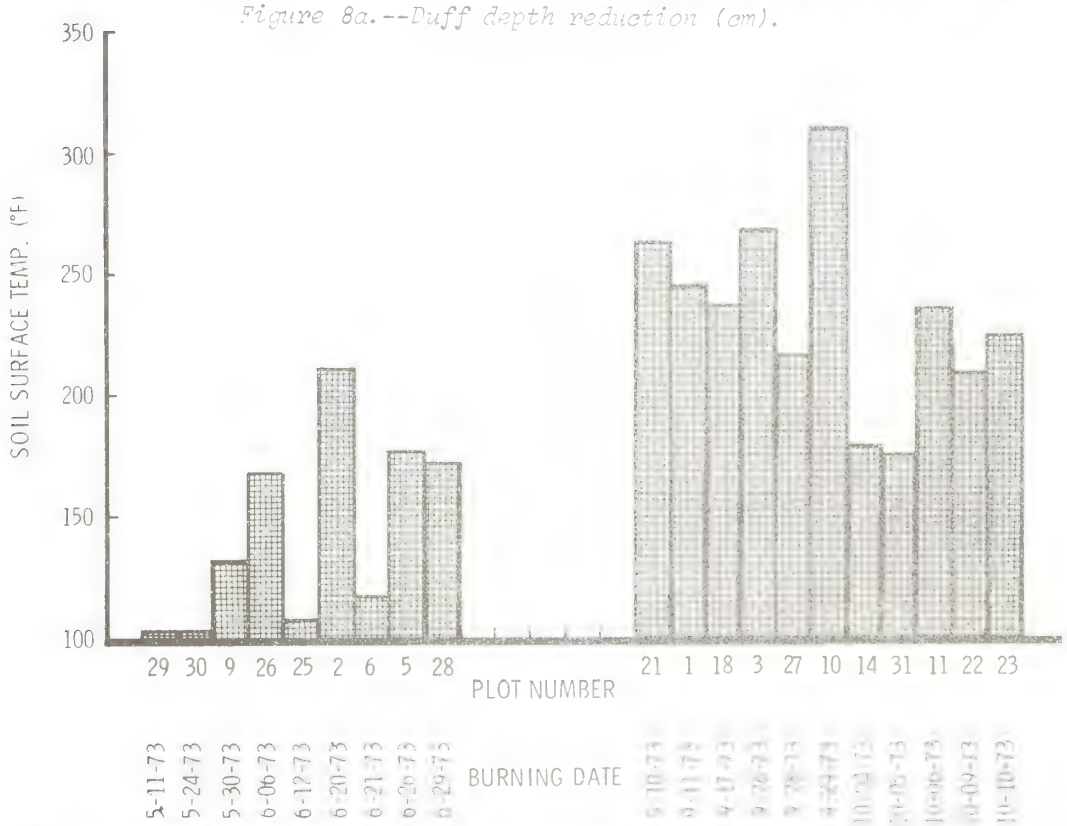


Figure 8a.--Duff depth reduction (cm).



DATA COLLECTION AND ANALYSIS

Shrub data used in this study were collected on twenty-six 1-m^2 quadrats within each burn plot. Two quadrats were randomly located about each of the 13 fuel inventory points. Shrub stems were tallied by species and stem size class before, and 1 and 2 years after the prescribed fires. A fire-pruned stem was considered to be one plant if it was alive at ground level. Sprouts originating from below the duff or soil level were considered to be separate plants.

Regression analysis was used to relate numbers of *Vaccinium globulare* present in all shrub inventory quadrats 1 and 2 years after fire to fuel, environmental, and fire effects variables and to prefire *Vaccinium* numbers. Computer program REX (Grosenbaugh 1967) was used to evaluate model alternatives. Two different sets of independent variables were used. One set contained variables that described fuel, moisture, and environmental conditions at the time of plot ignition. The second set contained variables that measured fire effects such as fuel reduction and duff and soil heating. Equations were developed for all 20 fires, and for spring and fall fires separately. A complete description of statistical procedures can be found in Miller (1976). Variable mean values, ranges, and standard deviations are listed in appendix 1.

RESULTS

Variability of Fire Effects

Because foliage of *Vaccinium* globulare is very nonflammable, plants are consumed by fire only after being dried and preheated by burning woody fuels (Rodney A. Norum personal communication 1976, Northern Forest Fire Laboratory). Dense stand of *Vaccinium* in large forest openings on the Lubrecht site did not burn because fuels were not present. Great heat input to the stem rhizome complex occurred in the vicinity of large amounts of dry fuel. Fire treatment was never uniform across a plot area because of fuel discontinuity.

The distribution of aboveground stems of *Vaccinium globulare* prior to fire treatment varied greatly among plots and among microsites on the same plot (table 1). Fire created a mosaic of effects, greatly increasing the variability already present. Plant response differed between microsites, with numbers increasing, decreasing, or changing very little. The percentage of plot area that fell into each of these classes ranged widely between plots burned in the spring and fall and between some plots burned within the same season.

Plot No.	Average number of stems per square meter: before fire	1 year after fire	2 years after fire	Number of plants: before fire	1 year after fire	2 years after fire	Percent change in number: 1973-1975
29	49.54	[illegible]	66.23	[illegible]	[illegible]	[illegible]	33.69
30	[illegible]	[illegible]	50.58	25	26	40.85	79.68
9	23.08	28.77	39.08	[illegible]	[illegible]	21.65	69.32
26	45.77	62.85	83.27	[illegible]	[illegible]	26	81.93
25	43.08	46.65	53.85	25	24	8.29	[illegible]
2	5.35	35.50	23.08	11	18	[illegible]	[illegible]
6	18.54	32.15	[illegible]	21	22	75.41	[illegible]
5	27.38	39.00	47.58	[illegible]	[illegible]	21	42.44	73.78
28	30.19	55.46	39.88	26	18	[illegible]	52.10
21	16.85	[illegible]	14.35	22	7	17	-66.25	[illegible]
1	3.96	2.31	2.08	[illegible]	[illegible]	[illegible]	-41.67	[illegible]
18	33.19	29.85	33.81	25	15	[illegible]	[illegible]	1.87
3	7.50	5.19	8.35	6	7	[illegible]	-5.08	[illegible]
27	18.73	37.54	46.62	25	18	[illegible]	[illegible]	148.91
10	34.65	38.08	47.35	[illegible]	[illegible]	23	9.90	[illegible]
14	97.96	92.96	[illegible]	26	26	26	-5.10	[illegible]
31	26.08	26.31	[illegible]	25	25	24	[illegible]	90.68
11	16.42	23.88	31.58	[illegible]	[illegible]	21	45.45	92.33
22	12.42	4.51	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
23	15.75	58.00	[illegible]	[illegible]	[illegible]	[illegible]	111.58	[illegible]

The number of *Vaccinium* stems present 1 full year after spring fires was always greater than before fire. New plants continued to appear in the second year (table 1). Sprouts sometimes appeared on quadrats where no aboveground stems existed before fire. These plants may have appeared from rhizomes that had not previously supported stems on those quadrats, or from rhizome tips that grew toward the surface. Only one spring fire removed plants from some quadrats for at least 2 years--the last fire, ignited on June 29, 1973.

At the end of the first growing season, *Vaccinium* numbers were less than before fire on 6 of the 11 fall burn plots. Little or no sprouting occurred on many quadrats. *Vaccinium* stems appeared in some of these quadrats the second growing season. Sprouts came from deeper levels, and sometimes may have originated from new or stimulated rhizome tips. Increases in plant numbers over prefire totals occurred on eight of the fall plots by the end of the second year (table 1). *Vaccinium* stem numbers did increase on some fall-burned plots, because plant density increased on some quadrats. However, all rhizomes were often killed on other areas of these same plots (fig. 9).

The depth of heat penetration controlled the number of sprouts that appeared. If a plant was burned off above ground level, several new shoots appeared as branches on one plant (fig. 10). Sprouts that appeared from laterally growing rhizomes functioned as separate plants (fig. 11). Greatly increased plant numbers resulted if stems were killed back below ground level and sprouts appeared from rhizomes (fig. 12). If heat penetrated to deeper levels with fewer rhizomes, sprout density was low (fig. 13).

Figure 9a.--Heavy preburn fuel loading.

Figure 9b.--Same site shortly after fire.

Figure 9c.--Abundant Epilobium angustifolium *and* Calamagrostis rubescens *regeneration 2 years later. Few* Vaccinium *sprouts were present.*

Figure 10.--Outgrowing buds form branches on partially killed stem.

Figure 11.--Stems killed back to ground level. Sprouts appear from rhizomes.

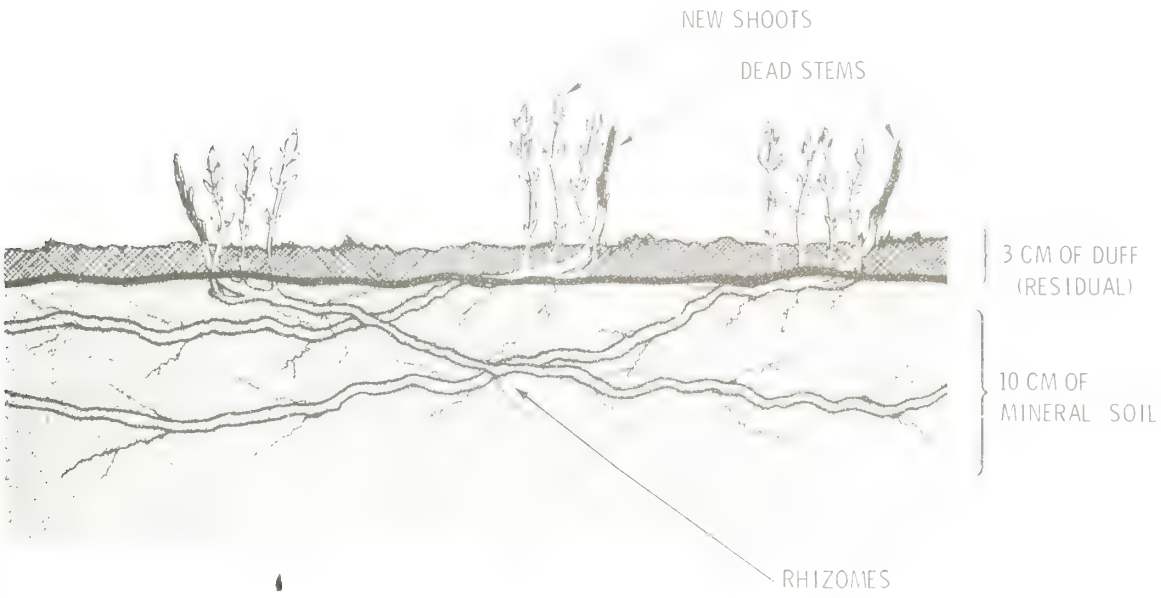


Figure 12.--Increased plant density resulted from heat penetration to slightly below the ground surface.

Figure 13.--Most rhizomes were killed on this deeply heated site. A few sprouts originated from rhizomes up to 22 cm below this surface. Some sprouts took longer than one growing season to appear.

Factors Related to Sprouting

Regression equations identified factors that could account for observed differenc in *Vaccinium* response to fire. Many significant equations containing many different variables were developed from each independent variable set for each time period. The variables that appeared in the four most significant equations for the 9 spring fires and for the 11 fall fires and the R^2 values of these eight equations are listed in tables 2 and 3. All of these independent variables were significant to at least the 0.05 probability level. The high statistical significance suggests that a strong relationship exists between these factors and the postfire *Vaccinium* community. Full statistics for these equations can be found in appendix 2.

Variables appearing in these equations were related to fire characteristics. Fuel loading and depth established the potential for heat release. Fuel moisture determined the degree of fuel ignitibility. Slope acted as wind, affecting fire sprea Relative humidity and ambient air temperature regulate moisture of very fine fuels, particularly when these fuels are dry (Steen 1963). Rhizome heating was limited by soil and lower duff moisture. Aspects of the heat regime created by fire are directly or indirectly measured by mean duff depth reduction, percent brush weight reduction, 1- to 3-inch fuel reduction, fire intensity, and mineral soil surface temperature.

Other variables appeared in other, slightly less significant equations. Preburn fuel loadings or fuel reduction in all other size classes, 0.635 to 2.54 cm (1/4 to 1 inch) diameter fuel moisture content, windspeed, and temperatures attained at and below the duff surface were all significant to at least the 0.05 probability level in equations for both spring and fall fires.

after spring
fires
after spring
after fall
fires
Number of
after fall
fires

spring fires
stems 1 year after
fall fires

Certain variables only occurred in equations for spring fires. Foliar moisture content may have inhibited fuel ignition when vegetation was fairly lush, but not in the fall when vegetative moisture content levels were considerably lower. Relative humidity and ambient air temperature may have been important in the spring because dry fine fuels were very sensitive to atmospheric humidity changes. Average fire intensity (as computed from crown scorch height) measured a characteristic of spring fires that was closely related to postfire *Vaccinium* numbers.

DISCUSSION OF RESULTS

The number of *Vaccinium* stems present after prescribed fire was more closely related to the number of stems present before fire treatment than to any other single factor. The more stems that protruded through duff and soil layers, the more sites were readily available for pruning by fire, and the more stems were likely to be replaced by one or several sprouts. High stem density before fire may have been associated with a denser rhizome network, increasing the probability that some new stems would be initiated from rhizomes which had not previously supported aboveground stems. All seasonal differences in sprouting were caused by differences in heat penetration at different times of the year. The number of buds stimulated to grow on each pruned stem or rhizome did not vary with season. The only seasonal response difference was that plants burned in the fall did not produce sprouts from released buds until the following spring.

The fairly consistent increases in *Vaccinium* numbers on most of the area of plots burned in the spring and the rhizome mortality which occurred on many fall fire plots were caused by differences in fuel loading and distribution, burning conditions, and duff and soil moisture levels. In the spring season, most fire heat came from consumption of fuels in smaller size classes. Large, sound fuels were too wet to burn. Large, rotten fuels were sometimes consumed by glowing combustion and some dry upper duff layers were removed. Lower duff and soil were wet enough to protect most rhizomes. In the fall, large fuels were dry enough to burn. Enough heat was released to dry and consume large amounts of duff. Soil moisture levels were too low to prevent soil heating and rhizome death. The importance of duff and soil moisture is emphasized by the fact that the only spring fire with rhizome mortality was ignited when duff and soil moisture content were very low.

A fire treatment most beneficial to *Vaccinium globulare* will remove senescent stems but cause minimal rhizome damage. Plants will be killed back to ground level if only fine fuels are consumed and lower duff and soil moisture content are high. The number of *Vaccinium* stems on three spring fire plots (plots 6, 26, and 30) increased from 80 to 120 percent over prefire totals. Conditions were dry enough for fire to carry, but not so dry that fire heat damaged rhizomes. Increases were not as great after other spring fires because fuels were too wet or duff and soil were too dry. One spring fire, ignited when conditions were fairly dry, caused a 900 percent increase in *Vaccinium* numbers in the first year after fire. However, this response may have been atypical because one-third of these plants died by the next year.

Fire will remove [illegible] from quadrats where heat penetrates smoldering fuels and duff reaches below the depth of all rhizomes. This occurred on many quadrats during fall fires, although sprouting was quite prolific on other quadrats not so deeply heated. *Vaccinium* was present on 35 to 68 percent fewer quadrats the first year after four fall fires (plots 1, 18, 21, and 22). After 2 years, plant numbers had not attained prefire totals on three of these plots. Fine fuels were too wet to be ignited on plot 18 (20.3 percent moisture content) but large fuels were dry enough to burn without small fuel combustion. Much rhizome death resulted from high duff consumption on plot 1, although it had a very light fuel loading (1.4 kg/m^2, about 6.4 tons/acre) because fine fuels, duff, and soil were extremely dry when the plot was ignited. Fall fires conducted in areas with very light fuel loadings when duff and fine fuels are wet will rarely kill rhizomes. *Vaccinium* was present on the same number of quadrats after a fall fire on a plot with a fuel loading of about 2.8 kg/m^2 (12.5 tons/acre) and a dense stand of *Vaccinium* plants. However, there was not enough fuel to carry fire and many plants were not pruned.

Moisture levels that favored or inhibited *Vaccinium* regeneration at the Lubrecht site are summarized in the following tabulation:

	Promotion (Percent)	*[illegible]ition*
0 to 0.635 cm fuel moisture content	< 12	19
Upper duff moisture content	[illegible]	70
Lower duff moisture content	[illegible]	70
Soil moisture content	[illegible]	19
Large fuel moisture	high--(will not burn, or difficult to ignite.)	low--[illegible] burn, easy to ignite.

Heat may not penetrate soil if soil moisture content is above a certain critical level. These results should be verified on other mesic sites with *Vaccinium*. Similar moisture levels may control the response of other rhizomatous species such as *Spiraea betulifolia* and *Symphoricarpos albus*.

Fire response of root crown sprouting shrubs such as menziesia (*Menziesia ferruginea*) and serviceberry (*Amelanchier alnifolia*) may be quite different from *Vaccinium* because of differences in the form, size, and location of sprouting sites. Also, it is not known whether these species have dormant buds or initiate new buds in response to fire pruning. There is a need to explore the relationship between fire intensity and postfire sprouting of these species and those of other forest types.

RECOMMENDATIONS

Spring burning is recommended to increase the density of *Vaccinium globulare* in Douglas-fir/western larch. Most spring fires will increase *Vaccinium* numbers on at least part of the burned area. Fires should not be conducted if lower duff and soil are dry.

If decreased *V. globulare* density is desired, burning should be done in the fall. Fire will usually kill rhizomes beneath fuel concentrations. Burning conditions which cause large amounts of duff reduction will result in the greatest decreases in *Vaccinium* numbers.

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APPENDIX

APPENDIX 1a. — Mean and Standard Deviation of Measured Variables

Variable	Spring fires		Fall fires	
	Mean	Standard deviation	Mean	Standard deviation
1. Number of *Vaccinium* spp. stems before fire (1973)	777.33	379.16	670.09	670.51
2. Preburn shrub weight (kg/m^2)	.15	.07	.07	.04
3. 0 to 1/4 inch (0 to 0.635 cm) preburn fuel weight (kg/m^2)	.07	.01	.10	.05
4. 1/4 to 1 inch (0.635 to 2.54 cm) preburn fuel weight (kg/m^2)	.14	.04	.15	.09
5. 1 to 3 inch (2.54 to 7.62 cm) preburn fuel weight (kg/m^2)	.43	.21	.57	.31
6. Rotten, 3 inch (7.62 cm) and larger preburn fuel weight (kg/m^2)	5.84	3.04	4.10	2.18
7. Sound, 3 inch (7.62 cm) and larger preburn fuel weight (kg/m^2)	1.11	1.20	.65	.98
8. Total, 3 inch (7.62 cm) and larger preburn fuel weight (kg/m^2)	6.95	2.82	4.75	2.76
9. Total preburn fuel weight (kg/m^2)	7.59	2.79	5.57	2.80
10. Preburn duff depth (cm)	7.24	1.20	7.05	1.85
11. Preburn herbaceous vegetation weight (kg/m^2)	.09	.06	.07	.03
12. Preburn dead fuel depth (cm)	16.59	8.68	16.15	8.65
13. Windspeed (mph)	2.56	3.09	2.64	2.66
14. Average slope (percent)	35.00	8.00	37.00	10.00
15. 0 to 1/4 inch (0 to 0.635 cm) fuel moisture content (percent)	10.74	2.02	20.58	6.55
16. 1/4 to 1 inch (0.635 to 2.54 cm) fuel moisture content (percent)	11.46	3.05	23.24	8.22
17. 0 to 1/4 inch (0 to 0.635 cm) fuel weight reduction (kg/m^2)	.02	.02	.04	.03
18. 1/4 to 1 inch (0.635 to 2.54 cm) fuel weight reduction (kg/m^2)	.06	.05	.08	.09
19. 0 to 1 inch (0 to 2.54 cm) fuel weight reduction (kg/m^2)	.09	.05	.12	.11
20. 1 to 3 inch (2.54 to 7.62 cm) fuel weight reduction (kg/m^2)	.08	.23	.28	.32
21. Total, 3 inch (7.62 cm) and larger fuel weight reduction (kg/m^2)	4.38	3.11	3.36	2.75
22. Total fuel weight reduction (kg/m^2)	4.55	3.14	3.83	2.70
23. Mean duff depth reduction (cm)	1.74	.49	3.85	1.74
24. Percent duff depth reduction (percent)	24.41	6.41	53.41	14.51
25. Fire intensity (kcal/sec/m^2)	105.07	63.01	71.68	44.84
26. Shrub weight reduction (percent)	64.47	20.95	53.92	20.91
27. Average mineral soil surface temperature (°F)	143.56	39.39	252.73	39.36
28. Adjusted soil surface temperature (°F)	60.56	50.98	174.36	56.83
29. Average duff surface temperature (°F)	252.44	62.19	359.27	66.42
30. Adjusted duff surface temperature (°F)	220.00	81.38	338.00	74.89
31. Average temperature at 2.5 cm below duff surface (°F)	191.00	56.39	320.27	78.05
32. Average temperature at 5.0 cm below duff surface (°F)	163.89	48.89	299.27	76.21
33. Average temperature at 7.5 cm below duff surface (°F)	141.78	51.98	263.91	79.25
34. Upper duff moisture content (percent)	40.57	21.45	70.55	28.86
35. Lower duff moisture content (percent)	89.99	42.84	79.11	23.02
36. Soil moisture content (percent)	29.09	11.55	12.51	3.97
37. Relative humidity (percent)	37.44	7.78	39.45	7.98
38. Understory foliage moisture content (percent)	259.00	57.46	128.31	16.67
39. Ambient air temperature (°F)	68.56	6.09	59.91	11.09
40. Ambient air temperature/soil moisture content	2.80	1.34	5.38	2.74
41. Number of *Vaccinium globulare* stems 1 year after fire (1974)	1,102.56	319.89	719.36	676.14
42. Number of *Vaccinium globulare* stems 2 years after fire (1975)	1,283.33	452.27	955.27	826.41

APPENDIX 1b. — Range of Measured Variables

Variable	Spring run		Fall run	
	Low	High	Low	High
Number of [illegible] stocks before time [1973	67	1,258	1,5	2,047
[illegible]				.18
[illegible]				.1
[illegible]				.6
[illegible]				.21
[illegible]				.31
[illegible]				.11
[illegible]				
[illegible]				
[illegible]			

APPENDIX 2. — Full Statistics for Regression Equations

Equation 1: Spring 1974

$Y(1) = 1104.2278 - 172.7340\ X(6) + 5619.8914\ X(37) - 392.1480\ X(40)$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(1)	Number of *Vaccinium* stems present 1 year after spring fires	923 to 1,634		
X(6)	Rotten, 7.62 cm (3 in) and larger, preburn fuel weight (kg/m^2)	1.62 to 10.52	5.1640	0.01
X(37)	Relative humidity (percent)	27 to 52	4.6770	.01
X(40)	Ambient air temperature/ Soil moisture content	1.38 to 5.14	5.7060	.01

$R^2 = 0.8700$

Standard error of the estimation = 145.8893

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	3	712221.740	237407.247	11.1544
Error	5	106418.480	21283.696	
Total	8	818640.220		

Since $F_{0.025}$ with 3/5 df is 7.76, the regression is deemed significant at the 0.025 level.

Equation 2: Spring 1975

$Y(2) = -2403.5965 - 219.0046\ X(6) + 66.7587\ X(36) + 8116.4752\ X(37)$

Variable	*Description*	*Range*		*Level of significance*
Y(2)	Number of *Vaccinium* stems present 2 years after spring fires	600 to 2,165		
X(6)	Rotten, 7.62 cm (3 in) and larger, preburn fuel weight (kg/m^2)	1.62 to 10.52	5.9220	0.01
X(36)	Soil moisture content (percent)	14.20 to 43.26	7.3990	.001
X(37)	Relative humidity (percent)	27 to 52	5.9692	.01

$R^2 = 0.9170$

Standard error of the estimation = 171.7840

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	3	1630219.200	543406.400	18.4145
Error	5	147548.770	29509.755	
Total	8	1777768.990		

Since $F_{0.005}$ with 3/5 df is 16.53, the regression is deemed significant at the 0.005 level.

Equation 3: Fall 1974

$$Y(3) = -498.3475 + 1.0430\ X(1) + 6754.6459\ X(3) + 70.3139\ X(8) - 28.5512\ X(12)$$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(3)	Number of *Vaccinium* stems present 1 year after fall fires	60 to 2,417		
X(1)	Preburn number of *Vaccinium* stems	103 to 2,547	16.1883	0.001
X(3)	0 to 0.635 cm (0 to 1/4 in) preburn fuel weight (kg/m^2)	0.05 to 0.15	4.0535	.01
X(8)	Total, 7.62 cm (3 in) and larger preburn fuel weight (kg/m^2)	1.08 to 10.75	4.2065	.01
X(12)	Dead fuel depth (cm)	6.97 to 30.31	4.8142	.01

$R^2 = 0.9812$

Standard error of the estimation = 119.5520

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	4	4485954.500	1121488.625	78.4659
Error	6	85756.090	14292.682	
Total	10	4571710.590		

Since $F_{0.001}$ with 4/6 df is 21.92, the regression is deemed significant at the 0.001 level.

Equation 4: Fall 1975

$$Y(4) = 442.0076 + 1.0742\,X(1) - 1520.2378\,X(14) - 31.5622\,X(15) + 12.7059\,X(35)$$

Variable	Description	Range		Level of significance
Y(4)	Number of *Vaccinium* stems present 2 years after fall fires	54 to 3,056		
X(1)	Preburn number of *Vaccinium* stems	103 to 2,547	13.9059	.001
X(14)	Average slope (percent)	23 to 50	2.8921	.05
X(15)	0 to 0.635 cm (0 to 1/4 in) fuel moisture content (percent)	8.03 to 35.20	3.3537	.02
X(35)	Moisture content of lower duff (percent)	22.78 to 103.19	4.5044	.01

$R^2 = 0.9821$

Standard error of the estimation = 142.6204

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	4	6707512.600	1676878.150	82.4400
Error	6	122043.540	20340.591	
Total	10	6829556.140		

Since $F_{0.001}$ with 4/6 df is 21.92, the regression is deemed significant at the 0.001 level.

Equation 5: Spring 1974

$Y(1) = 1173.3210 + 0.6756\ X(1) - 451.6954\ X(23) + 1.8632\ X(25)$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(1)	Number of *Vaccinium* stems present 1 year after spring fires	923 to 1,634		
X(1)	Preburn number of *Vaccinium* stems	87 to 1,288	7.4264	0.001
X(23)	Duff depth reduction (cm)	1.2 to 2.7	5.2239	.01
X(25)	Fire intensity (kcal/sec/m^2)	33.66 to 213.76	2.6770	.05

$R^2 = 0.9474$

Standard error of the estimation = 92.8019

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	3	775579.230	258526.410	30.0186
Error	5	43060.990	8612.198	
Total	8	818640.220		

Since $F_{0.005}$ with 3/5 df is 16.53, the regression is deemed significant at the 0.005 level.

Equation 6: Spring 1975

$Y(2) = 555.6506 + 1.4142\ X(1) + 3.6020\ X(25) - 11.2802\ X(26)$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(2)	Number of *Vaccinium* stems present 2 years after spring fires	600 to 2,165		
X(1)	Preburn number of *Vaccinium* stems	87 to 1,288	9.9368	[illegible]
X(25)	Fire intensity (kcal/sec/m^2)	33.66 to 213.76	3.4798	.02
X(26)	Percent shrub weight reduction	36.59 to 95.44	3.7456	.02

$R^2 = 0.9535$

Standard error of the estimation = 128.2812

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	3	1695037.600	565012.533	34.1478
Error	5	82730.384	16546.077	
Total	8	1777767.984		

Since $F_{0.001}$ with 3/5 df is 33.20, the regression is deemed significant at the 0.001 level.

Equation 7: Fall 1974

$Y(3) = 807.9676 + 0.7183\ X(1) - 885.4242\ X(20) - 4.8737\ X(27) + 67.7194\ X(36)$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(3)	Number of *Vaccinium* stems present 1 year after fall fires	60 to 2,417		
X(1)	Preburn number of *Vaccinium* stems	103 to 2,547	8.2441	0.001
X(20)	2.54 to 7.62 cm (1 to 3 in) fuel weight reduction (kg/m^2)	-0.02 to 1.05	4.7649	.01
X(27)	Average temperature at mineral soil surface (°F)	175 to 310	2.9972	.05
X(36)	Soil moisture content (percent)	5.74 to 18.41	3.8224	.01

$R^2 = 0.9692$

Standard error of the estimation = 153.0757

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	4	4431117.500	1107779.375	47.2760
Error	6	140593.080	23432.181	
Total	10	4571710.580		

Since $F_{0.001}$ with 4/6 df is 21.92, the regression is deemed significant at the 0.001 level.

Equation 8: Fall 1975

$Y(4) = 605.4407 + 0.9297\ X(1) - 774.6745\ X(20) - 4.6911\ X(28) + 60.7141\ X(36)$

Variable	*Description*	*Range*	*"t"*	*Level of significance*
Y(4)	Number of *Vaccinium* stems present 2 years after fall fires	54 to 3,056		
X(1)	Preburn number of *Vaccinium* stems	103 to 2,547	12.0059	0.001
X(20)	2.54 to 7.62 cm (1 to 3 in) fuel weight reduction (kg/m^2)	-0.02 to 1.05	4.5531	.01
X(28)	Adjusted mineral soil surface temperature	50 to 262	4.9959	.01
X(36)	Soil moisture content (percent)	5.74 to 18.41	4.2349	.01

$R^2 = 0.9817$

Standard error of the estimation = 144.4982

Source of variation	*df*	*SS*	*MS*	*F*
Due to regression	4	6704277.800	1676069.450	80.2725
Error	6	125278.410	20879.734	
Total	10	6829556.210		

Since $F_{0.001}$ with 4/6 df is 31.09, the regression is deemed significant at the 0.001 level.

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Miller, Melanie

1977. Response of blue huckleberry to prescribed fires in a western Montana larch-fir forest. USDA For. Serv. Res. Pap. INT-188, 33 p. Intermountain Forest and Range Experiment Station, Ogden, Utah 84401.

In a western larch Douglas-fir forest type in western Montana, 6 spring and 11 fall understory burns were conducted. The number of Vaccinium globulare blue huckleberry stems present before burning and 1 and 2 years after burning were related to fuel loadings, moisture content of fuel, duff and soil, environmental conditions, fuel reduction, fire intensity, and temperatures reached at the duff and soil surface during the fires. Because moist duff and soil protected rhizomes from fire heat, increases in plant numbers always resulted from spring fires. The large amounts of heat released by fall fires caused rhizome mortality on plots where levels of duff and soil moisture were low.

KEYWORDS: fire regeneration, burn effects, shrub response, larch-fir forest

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MATURATION OF WESTERN LARCH CONES AND SEEDS

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USDA Forest Service Research Paper INT-189
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RESEARCH SUMMARY

Weekly cone collections from late July through September 1964 and 1965, and irregular collections in 1966 and 1967 were used to evaluate specific gravity and moisture content as indices of cone maturity. Although both indices decreased with advancing cone maturity, neither index gave a firm indication of seed maturity, but they did predict when cones would open. The ratio of embryo length to embryo cavity length gave the best estimate of seed maturity in 1964. Cones on a given tree all open within a short period of time, but the opening of cones among individual trees within a stand may vary greatly. Larch cone collections can begin in mid-August; if cones are stored under well-ventilated conditions for several weeks before seeds are extracted, viability remains high.

INTRODUCTION

Western larch (*Larix occidentalis* Nutt.), a conifer prized for its beauty and timber value, grows in the Northern Rocky Mountains west of the Continental Divide. Larch cones are small and widely scattered throughout the crowns, making collection both difficult and time consuming. Good cone crops, with higher than average seed viability (Shearer 1959), occur on the average of every 5 years (range of 1 to 12 years). Usually, a concerted effort is made to collect these cones during years of abundance to supply the needs for seeding and planting during intervening years of scarcity.

Specific gravity and moisture content are successfully used to identify seed maturity in other conifers: true firs (Franklin 1965; Pfister 1967; Oliver 1974); pines (Eliason and Hill 1954; Krugman 1966); and spruce (Cram 1956; and Cram and Worden 1957). Other indices have been used: cone firmness, color, and seed brittleness (Crossley 1953); and reducing sugar content of seed (Rediske 1961, 1969); crude fat concentration (Rediske and Nicholson 1965); ratio of embryo length to embryo cavity (Oliver 1974); and seed weight (Olson and Silen 1975).

The purpose of this study was to identify a reliable index (specific gravity, moisture content, cone color, and embryo length) of western larch seed maturity and to determine if the period of cone collection (usually from late August through mid-September) could be extended. In addition, some possible climatic factors influencing cone maturation and seed viability were investigated.

METHODS

Five western larch trees varying in age from 55 to 70 years were selected in July 1964 for sampling (fig. 1). The trees grow on gentle, northerly facing slopes at about 4,000 feet in elevation on the Lolo National Forest in lower Pattee Canyon near Missoula, Montana. They varied in diameter from 8.6 to 11.6 inches and in height from 50 to 64 feet. Selection was based on: (1) each tree having at least 300 cones; (2) a range of cone colors--two trees with deep reddish-brown cones, two trees with green cones, and one tree with brown cones (a second tree with brown cones was not found); and (3) dominant trees that were easily climbed with ladders.

Figure 1.--Tree G-1 in mixture with Douglas fir, ponderosa pine, and other western larch

Table 1.--[illegible]

Data	Year of cone collection			
	1964	1965	1966	1967
Specific gravity (SG)	18	5	0-5	6
Moisture content (MC)	4	5		
Weight per 1,000 seeds (grams)	21	4-9	0-5	6
Germination (percent)	21	4-9	0-5	6
Average seeds per cone	21	4-9	0-5	6
Seed extracted after cone storage	-	4-9	0-5	
Seeds per SG class	14			
Seed wt. per SG class (grams)	14			
Frequency distribution of SG	14			
Seed extracted on day cones were collected	11			

[1]Number of collection dates: 1964, 11; 1965, 7; 1966, 1; 1967, 6.

The trees were sampled from 1964 to 1967 to study yearly variation in the cone maturity and time of seed release. Table 1 shows the data derived by year of cone collection and the number of cones sampled.

At each collection, cones free from visible insect damage were picked randomly throughout the crown of each tree. The cones were placed in plastic bags to reduce moisture loss and taken immediately to the laboratory.

For all cones collected, specific gravity was determined from the loss in weight of each cone in water. Samples of the cones collected in 1964 and 1965 were ovendried at 212° F for 20 hours and moisture content was calculated.

In 1964 over half the cones collected each week were segregated into specific gravity classes and dried for 24 hours at 113° F. Seed was then extracted in each class by shaking the cones. The seeds were dewinged, weighed to the nearest 0.001 gram, and counted. For each specific gravity class, weight per 1,000 seeds and the average number of extracted seeds per cone were calculated. The seeds were kept in envelopes at room temperature until the germination tests.

Depending on the year, some or all the cones were stored in well-ventilated paper sacks in a cool, dark room until the fall or winter, when they were dried for 24 hours at 113° F and the seeds extracted, dewinged, and weighed to the nearest 0.001 gram. The average number of seeds per cone and weight per 1,000 seeds were calculated for each group of cones. The seeds were kept in envelopes at room temperature until the germination tests. In 1976 ratio of embryo length to cavity length was determined from residual 1964 seed that was stored in the envelopes.

Differences in seed viability caused by variation among the five trees, the 10 collection dates, and the two extraction times were determined in germination tests that were replicated three times. Seeds were evenly spaced on blotter paper in petri dishes (100 seeds per dish) when there was enough seed. The seeds were moistened thoroughly with water then stratified at 55° F. The dishes were then arranged in a randomized block design and incubated at 80° F ± 1° F in constant, low-intensity, incandescent light. Germination (seeds with radicle emergence 0.1 in) was recorded

at irregular intervals. The nongerminated seed was then classified as sound, rotten, or empty.

The 1964 germination data were analyzed in a multivariate analysis of variance to determine the significance of the tree, collection date, and extraction time differences. Analysis of variance was used to analyze the germination data from 1965 and 1967; the 1966 data were not analyzed.

RESULTS

Cone Ripening and Ripeness Indicators

In 1964, the western larch cones increased in length and width through August 10, then decreased in these dimensions through the final collection. The cones ranged in length from 1.00 to 2.00 inches (average 1.42 inches) and in width from 0.60 to 1.05 inches (average 0.80 inch). Cone size differences by tree were consistent in the 4 years of study.

Changes in specific gravity, moisture content, and color all signaled the maturing of western larch cones through August and September. Climatic factors such as rainfall and temperature modified the time of cone opening.

Embryo Development

The megagametophytes were milky in late July but were firm by early August. As shown in the following tabulation, embryo development (ratio of embryo length to cavity length) was complete by mid-August for all seeds; embryos in seeds from three of the five trees were fully developed by early August:

1964 date	*Average* *Percent*	*Standard deviation* *Percent*
July 29	83	2
August 3	86	5
August 10	95	4
August 17 and 24	99	1
August 31 to September 28	100	0

Specific Gravity and Moisture Content

In 1964 and 1965, specific gravity (fig. 2) and moisture content of larch cones were closely related and remained relatively constant from late July to early September, then decreased rapidly through the final measurement at the time of seedfall. Correlation values for these 2 years ranged from $r = 0.94$ to $r = 0.99$ for individual trees, with a pooled $r = 0.99$ (fig. 3). Because of this close correlation, only specific gravity was determined for the cones in 1966 and 1967.

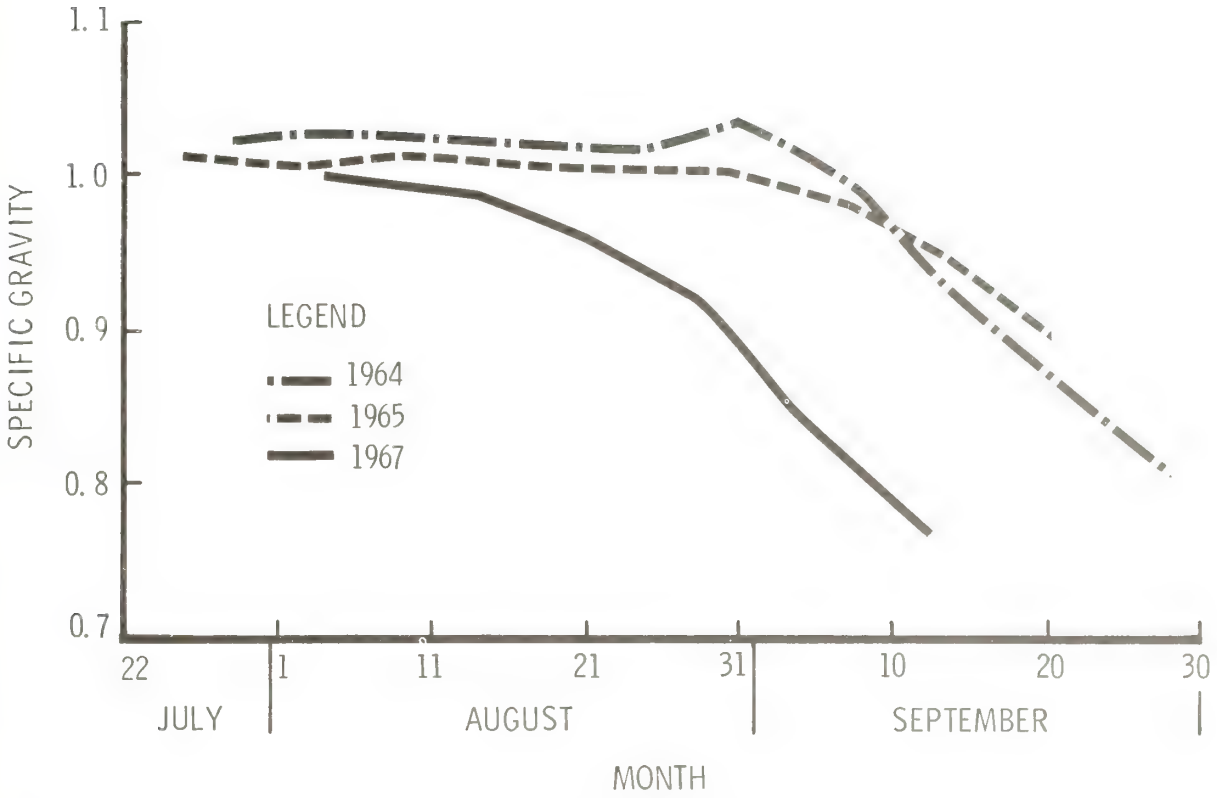

Figure 2.--Average cone specific gravity by collection date; 1964 and 1965 were wet years, 1967 was a dry year.

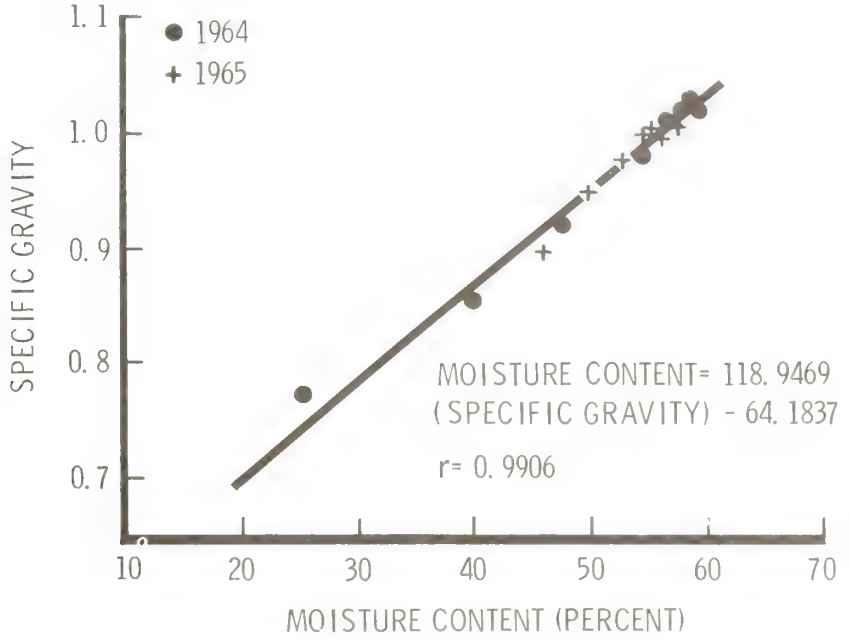

Figure 3.--Relationship of specific gravity to moisture content of western larch cones harvested in 1964 and 1965.

The variation in specific gravity and moisture content among the cones in August was small but increased rapidly as the cones dried in September. Most of the variance in the September data resulted from between-tree rather than within-tree differences. Specific gravity of cones decreased at a rate that was characteristic of each tree regardless of year. Trees with cones that decreased in specific gravity most rapidly also began seedfall earliest. Moisture content of the cones ranged between 55 and 60 percent throughout August then decreased rapidly in September.

Cone Color

As cones matured and finally opened, they lost the reddish or greenish hues and became more yellow or brown. At the time of seedfall cones collected from these five trees were nearly the same color.

Climatic Influence

The rate of decrease in cone specific gravity and moisture content during August and September prior to cone opening was influenced by the amount and frequency of rain and the average air temperature or heating degree-days. (One heating degree-day is here defined as a day on which the mean daily temperature is 1 degree below 65° F.) Above-average rainfall and below-average temperature (higher number of heating degree-days) characterized the summers of 1964 and 1965, whereas below-average rainfall and above-average temperature (lower number of heating degree-days) typified the summer of 1967 (table 2). Specific gravity decreased more rapidly during the hot, dry summer of 1967 than in the cooler, moister summers of 1964 and 1965 (fig. 2). The difference in specific gravity between 1964 and 1965 was not statistically different. However, the release of seed occurred later in September 1965 than in 1964; greater rainfall and lower temperature (more heating degree-days) were recorded in September 1965 than in 1964. An exact comparison between those 2 years was not possible because insufficient numbers of cones were produced in 1965 to permit collections until cones had opened.

Table 2.--*Temperature and precipitation patterns at the National Weather Service Station, Missoula, Montana, by year*

Year	Month	Precipitation		Temperature		Heating degree-days	
		Amount	Departure from normal	Mean	Departure from normal	Sum	Departure from normal
		Inches	*Inches*	*°F*	*°F*		
1964	July	0.94	+0.09	66.2	-0.8	31	- 3
	August	1.84	+1.12	60.8	-4.0	153	79
	September	.51	- .51	51.1	-4.3	409	106
1965	July	1.59	+ .74	65.0	-2.0	44	10
	August	2.24	+1.52	64.1	- .7	88	14
	September	2.11	+1.09	47.8	-7.6	509	206
1967	July	.40	- .45	70.0	+3.0	2	- 32
	August	Trace	- .72	71.2	+6.4	4	- 70
	September	.49	- .53	62.2	+6.8	116	-187

SEED

Western larch cones on the trees opened in late summer at a specific gravity of 0.80 to 0.85 and a moisture content of 35 to 40 percent. Usually all the cones on a tree opened within a week of one another. However, considerable variation occurred between trees, as shown for 1964 and 1967, by date cone opening was first observed:

	1964	*1967*
G-1	September 14	August 28
R-1 and I-1	September 21	September 4
G-2	September 28	September 12
R-2	After October 1	After September 12

Cones on tree G-1 opened about a week before cones on trees R-1 and I-1; cones on trees G-2 and R-2 opened still later as shown in the tabulation. Cones on all trees opened about 2 weeks earlier in 1967 than they did in 1964. In 1965, sampling depleted the cone crop prior to seedfall. Left on the trees, cones probably would have begun seed dispersal about a week later than in 1964. In 1966, only enough cones were produced for one collection.

Number and Viability

The number of seeds extracted from the cones and their viability were dependent on at least three factors: (1) location or possible inherent characteristics of the parent tree; (2) stage of maturity when cones were picked (table 3, fig. 4); and (3) the length of time between cone collection and seed extraction (table 4 [compare means], fig. 5).

Tree differences.--The average number of seeds extracted per cone varied by tree (table 3). Consistently fewer seeds were extracted from cones of tree G-1 than from the other trees. The scales on cones picked from tree G-1 failed to fully open; scales on the cones picked from the other trees opened easily. These characteristics were also consistent among cones picked from the trees in 1965, 1966, and 1967.

Table 3.--*Mean number of seeds per cone extracted on October 30, 1964, by date cones were picked*

Collection date, 1964	Mean	Range	Standard deviation
July 29	62	91-33	18
August 3	70	84-39	18
10	75	90-41	21
17	86	105-57	18
24	80	95-63	15
31	86	98-71	10
September 8	100	113-88	10
14	103	115-87	13
21	89	102-63	10
28	72	104-56	19

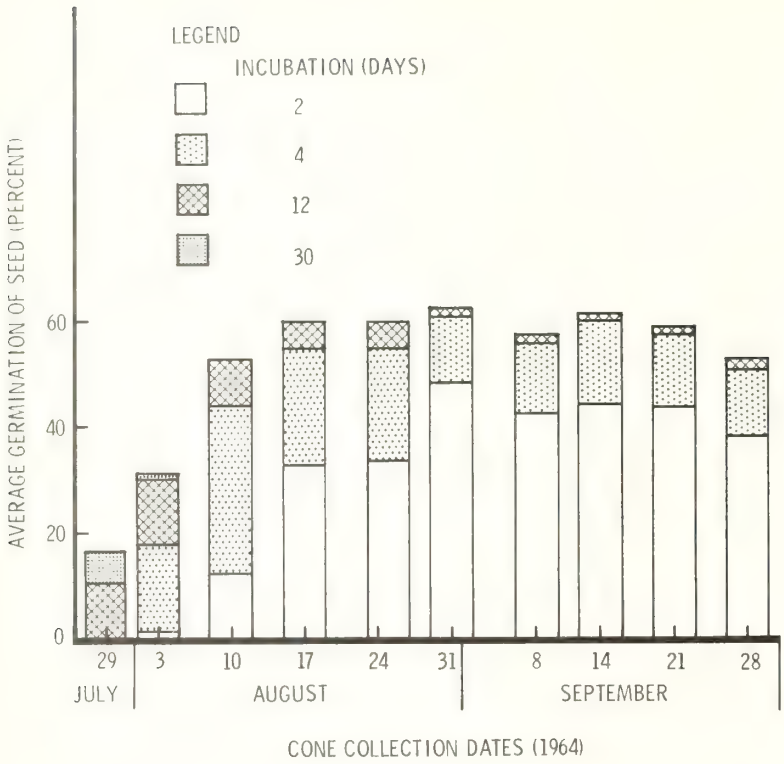

Figure 4.--Effect of cone collection dates on germination of western larch seed extracted October 30, 1964; 2, 4, 12, and 30 days after the start of incubation.

Table 4.--*Average number of western larch seeds per cone extracted the day of collection by specific-gravity class at 10 weekly intervals in 1964*

Cone specific gravity	7/29	8/3	8/10	8/17	8/24	8/31	9/8	9/14	9/21	9/28
	Number									
1.070 to 1.099						73				
1.040 to 1.069	41	40	71	80	90	75	100			
1.010 to 1.039	25	55	52	52	89	74	101	90		
0.980 to 1.009	37	8	24	35	74	62	89	80	103	
0.950 to 0.979							85	84	100	
0.920 to 0.949							87	72	90	93
0.890 to 0.919							81	70	98	91
0.860 to 0.889							105	57	98	91
0.830 to 0.859								50	92	97
0.800 to 0.829								36	81	
0.770 to 0.799								60	69	91
0.740 to 0.769								80	51	93
0.710 to 0.739								46	71	79
<0.710									72	80
Average	29	49	49	50	84	72	91	71	88	90
Average number of seed from cones stored until October 30	62	70	75	87	80	87	100	103	89	72

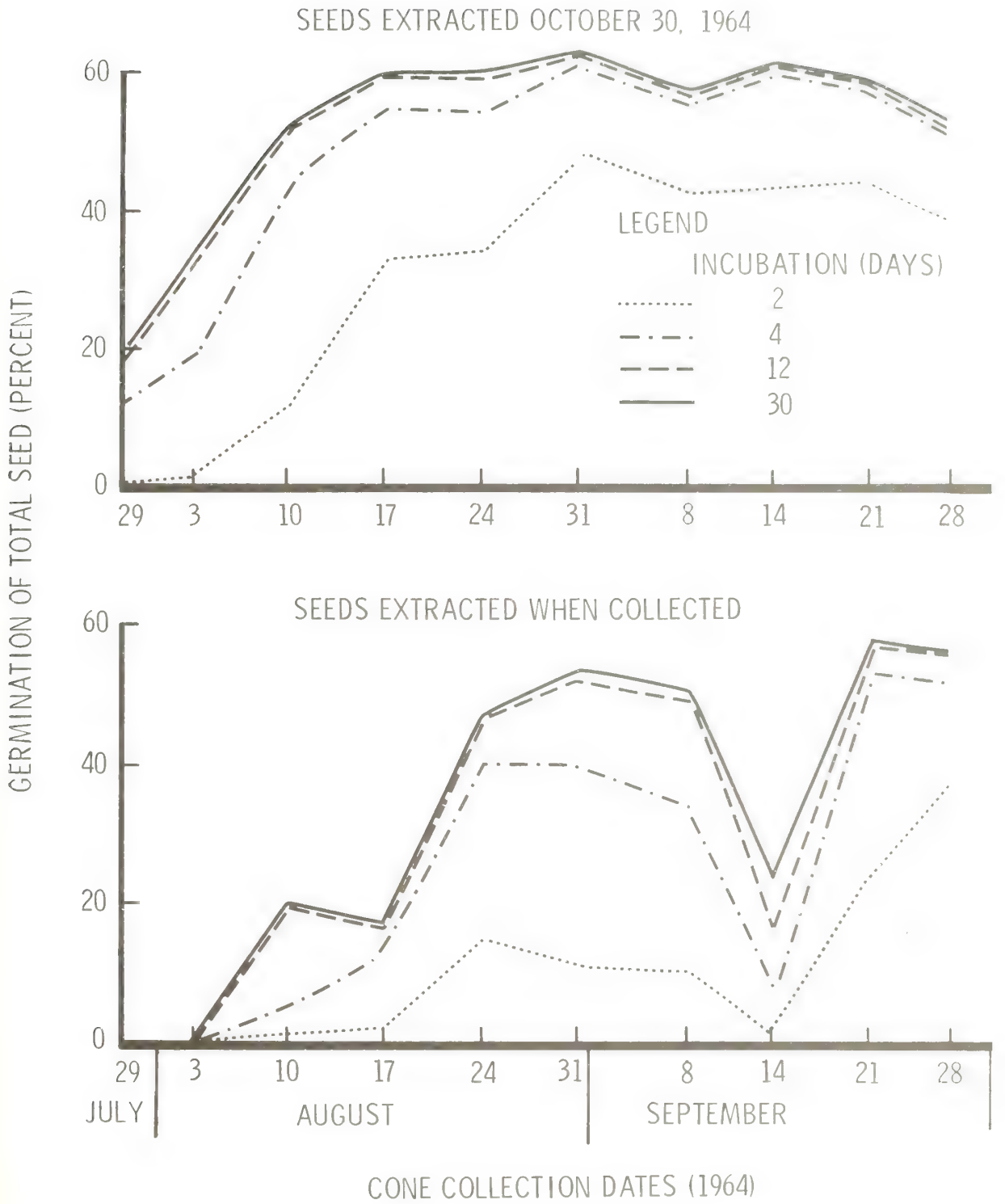

Figure 5.--Effect of extraction time and collection date on germination of western larch seed; 2, 4, 12, and 30 days after the start of incubation.

As shown in the following tabulation, the greatest germination of seed collected in 1964, 1965, and 1967 from the five western larch trees averaged 55 percent and ranged between 79 and 35 percent (standard deviation, 13 percent). Seed viability from the trees fell into two groups. Three trees, growing within 500 feet of one another, averaged 62 percent germination (standard deviation, 12 percent) in the 3 years. The other two trees grew within 100 feet and averaged 44 percent germination (standard deviation, 7 percent) during the same period.

	Year of collection			
	1964	*1965*	*1967*	*Average*
	Percent			
Average	66	49	50	55
Standard deviation	14	10	9	13

Date of cone collection.--The number of seeds per cone extracted after storing the cones until October 30, 1964, generally increased from the July 29 through mid-August collections--one tree through early September (table 3). Cones picked from two trees on July 29 opened poorly and most seeds were trapped inside. The low number of seeds shown in table 3 from September 14 to 28 probably resulted from the loss of some seeds prior to picking the cones. (Larch cone scales open and close easily, depending on humidity and temperature, and it is difficult to identify closed cones that previously opened). Some cones with below-average specific gravity and below-average seed yield were infested by insects that prevented the scales from flexing normally and releasing the seeds. Heavy deposits of resin on scales of some cones also prevented normal release of some seed.

Viability of seed was also influenced by the date the cones were picked (fig.4). As shown in the following tabulation, trees with the highest seed viability (G-1, R-1, I-1) usually produced cones that matured earliest (collection date when seed reached at least 90 percent of the maximum germination recorded).

Tree identification	*Date of cone maturity by collection year*		
	1964	*1965*	*1967*
G-1	August 10	August 30	August 4
R-1	August 10	August 30	August 21
I-1	August 10	September 7	August 4
G-2	August 17	September 7	August 28
R-2	August 24	September 7	August 21

This tabulation also shows that the date of cone maturity varied by year; i.e., cones matured in mid-August in 1964 and 1967 and in early September in 1965.

Total germination and germinative energy (percentage of seeds that germinated within 4 days) increased through the August 31 collection (fig. 4). The average germinative energy was very poor from July 29 collections, but total germination varied widely by parent tree (R-1, 61 percent; G-1, 32 percent; I-1, 20 percent; G-2, 8 percent; and R-2, 0 percent). Similar trends occurred in 1965 and 1967 except highest germination in the 1965 seed occurred in seed collected 2 weeks later than in 1964.

Time of extraction.--Seed quantity and quality were not only influenced by when the cones were picked but also by when the seeds were extracted from the cones. In 1964, cones dried the same day picked usually yielded fewer seeds than the cones stored until October 30. Cones picked July 29 did not open fully, especially when seeds were

extracted immediately. This problem persisted through August 17 (the next three collections) among cones dried without storage and through August 10 (the next two collections) among cones stored until October 30. The number of seeds released from the cones picked on any one date usually declined with decreasing cone specific gravity (table 4), because some lighter cones had already shed some seed.

Considerable variation existed between trees in the release of seed from cones stored until October 30. For example, seed release from cones of tree G-1 was low (31 seeds per cone) from the July 29 collection and increased slowly each subsequent week to a high of 88 seeds per cone from the September 8 collection. Seed release started low (33 seeds per cone) for tree R-1 but by August 17 released over 80 seeds per cone. The remainder of the trees produced cones that readily opened after all collections.

A trend of increasing seed weight with increasing specific gravity is apparent in table 5. Seed weight increased until mid-August, then declined. Seeds extracted from cones the day of collection were heavier than seeds extracted from cones collected the same day but stored until October 30.

Storage of cones prior to extraction prolonged the maturing processes in the seed and increased its viability when compared to seed extracted the day of cone collection (fig. 5). Total germination and germinative energy of seed extracted the day the cones were picked was significantly reduced except for the last two collections of 1964. Cones collected on July 29 and August 3, 1964, from trees other than tree R-1 yielded seed of low viability regardless of when the seed was extracted. Seeds extracted immediately following the cone collections on July 29 and August 3 had less than 1 percent germination. Cones collected on July 29 but stored until the end of October yielded seed that varied in viability from no germination (tree R-2) to 46 percent germination (tree R-1). The drastic decline in viability of seed collected and extracted on September 14 is unexplained. The 1964 data suggest that cones collected mid-August and stored were sufficiently mature to provide seed comparable in viability to cones collected later. As a result of the comparison in 1964, all cones were stored in 1965, 1966, and 1967.

Table 5.---

Specific gravity class											
1.070 to 1.099											3.60
1.040 to 1.069	3.34			3.49	3.59						
1.010 to 1.039	2.93	2.94	3.23	3.54	3.41		3.1	3.34			
0.980 to 1.009	2.68	2.74	3.10	3.11			3.17	3.36	2.73		
0.950 to 0.979							3.08	2.97			2.99
0.920 to 0.949									3.20		3.19
0.890 to 0.919								3.45	3.26	3.06	
0.860 to 0.889										3.34	
0.830 to 0.859								3.11		2.89	3.09
0.800 to 0.829											
0.770 to 0.799											
0.740 to 0.769								3.03		3.02	
0.710 to 0.739								2.68	2.81		
<0.710									2.50		
Weighted mean	2.88	2.97						3.28	3.10	3.01	

Germinative energy was also substantially increased by storing the cones picked from July 29 through August 17, 1964, (fig. 5). Seed extracted on July 29 and August 3 failed to germinate, seeds extracted August 10, August 17, and September 14 has low germination, and seeds extracted on all other dates had near normal germination. Seed from cones collected August 10 or later and stored had similar germination (fig. 5).

For seeds extracted October 30, 1964, the incidence of seed decay among ungerminated seed at the completion of the germination test was lowest from cones collected on August 17 or later (fig. 6). The time of extraction made little difference for the September cone collections except for the unexplained drop in viability of the seeds (and a corresponding increase in decay) collected on September 14.

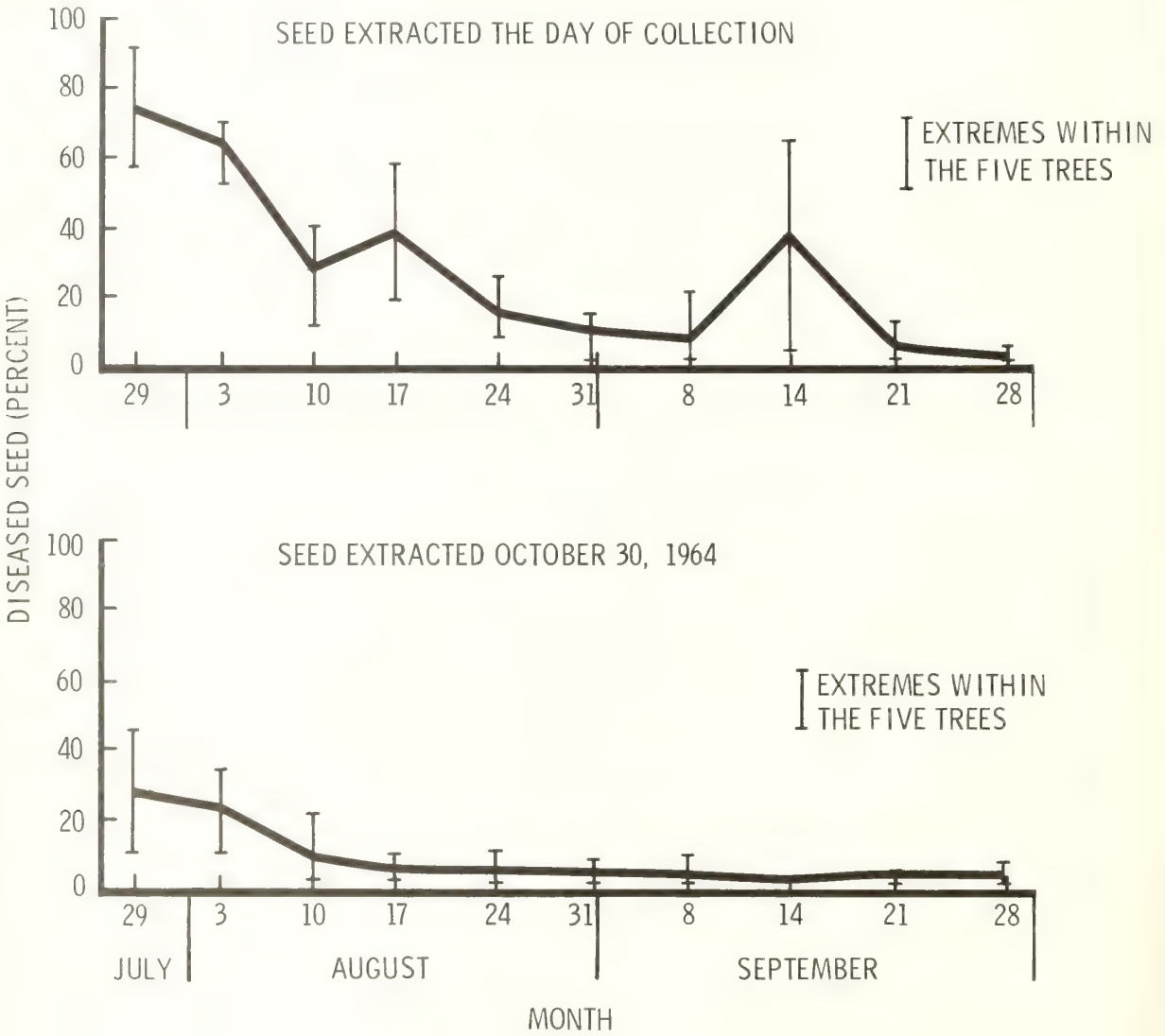

Figure 6.--Average percent of ungerminated seed from five trees that were classified as "diseased" at the completion of the germination test by cone collection date and when seed was extracted.

Table 6.--[illegible]

Collection year	July 26-31	Aug 1-7	Aug 8-14	Aug 15-21	Aug 22-28	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	Grams per 1,000 seeds									
1964	2.47	2.82	3.01	3.13	3.04	3.14	3.03	3.02	2.99	2.82
1965	2.53	2.65	--	--	2.44	2.66	2.86	2.88	2.88	
1966	2.14	--	--	--	--	-				
1967	--	2.18	2.37	2.50	2.50	2.72	--	2.48		

Seed weight.--Weight (grams per 1,000 seeds) of seeds extracted the day of cone collection varied by collection date and specific gravity of cones (table 5). The greatest seed weight was achieved near the end of August. At any given cone collection date, the heavier seeds were usually extracted from cones with high specific gravity.

Seed extracted from cones that were stored until October 30, 1964, average 93 percent as heavy as seeds extracted the day of cone collection (table 6--compare 1964 data with weighted means shown in table 5). Seed extracted from cones in subsequent years were lighter than seeds extracted in 1964.

DISCUSSION AND CONCLUSIONS

Many factors (natural and man-influenced) combine to affect the amount and quality of western larch seed collected. The continual demand for quality seed together with its high cost dictates that cones be collected during the infrequent years of heavy production when seed is mature, but prior to cone opening.

The rate at which cones mature is influenced by the average temperature during the growing season. Cones mature faster during summers of above-average temperature (such as 1967) than in summers of below-average temperature (1964 and 1965). Once the cones mature, prolonged periods of rain or high humidity can delay cone opening.

The ratio of embryo length to cavity length in 1964 gave the best indication of seed maturity. This has also been shown for true firs (Pfister 1967; Oliver 1974).

Based on 3 years of data, specific gravity and moisture content do not accurately indicate when cones are sufficiently mature to pick. These indicators did accurately predict when cones were to open (specific gravity about 0.820, moisture content about 35 percent). Because of the wide range in cone colors within and among individual trees as cones mature, color is a poor indicator of cone maturity.

Larch cones can be picked from about mid-August and yield high viability seed if the cones are stored under well-ventilated conditions for a few weeks prior to seed extraction. This allows 3 to 6 weeks for collection prior to cone opening. Because mold is a severe problem in storing cones, particularly immature cones, sacks should be spaced so that air can circulate between them. If seeds are to be extracted immediately, cone collection should be deferred until about September 1.

Trees bearing "early-opening" cones begin to disperse seed 2 to 3 weeks before trees bearing "late-opening" cones. The cones on any given tree all open within a short time, perhaps within a week. Because only five trees were sampled, it was not evident if cone opening within a stand followed a normal curve or was skewed. Seed dispersal studies in western larch forests have shown that most sound larch seed is dispersed by mid-October. Seeds dispersed later usually have low viability and come from either the base or the apex of the cone.

Seed yield and viability are dependent on maturity of cones at harvest. When seeds were extracted the day of cone collection, both seed yield and viability increased from July 29 through August 31, 1964. However, when seed extraction was delayed until October 30 for each of these same collections, the number of seeds recovered and their viability were further increased. When seed must be extracted immediately following cone collection, then the late-August or early-September collections are best.

Germination tests showed that stored cones yielded seed of higher viability and less subject to disease during germination than seed extracted immediately following cone collection. Further, total germination was nearly the same for seeds collected at any date from mid-August until cone opening but germinative energy was greatest from late August until cone opening. The number of viable seeds was influenced by location of the trees, possibly caused by differences in pollination. Greatest seed weight occurred in mid-August regardless of when seeds were extracted. As a result, harvest of high-quality seed could have begun at least a month before seedfall in 1964.

The consistently lower weight of seed extracted October 30 compared with seed extracted the day of cone collection indicates a decrease, possibly of carbohydrates or other nutrients, from the seeds while the cones were stored. The difference cannot be attributed to water loss because all cones were dried similarly. Rediske (1961) showed reducing sugar decreased as seeds matured in picked cones. In addition, seed weight in subsequent years was less than in 1964, probably a reflection of fewer sound seeds.

Further studies can identify the optimum length of time for cone storage to extract high quantity and quality seed.

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Cone maturity in western larch in western Montana was most accurately predicted by the ratio of embryo length to seed cavity length. Neither moisture content nor specific gravity proved to be an index of cone maturity; however, cones predictably opened at a specific gravity of about 0.820 and a moisture content of 35 percent. In western Montana cone collection can begin in mid-August. Permitted to mature for several weeks in mold-inhibiting storage, cones will yield high percentages of viable seed.

KEYWORDS: Larix occidentalis, cone collection, germination tests, seed extraction

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DECLINING ROOT STRENGTH IN DOUGLAS-FIR AFTER FELLING AS A FACTOR IN SLOPE STABILITY

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FOREST ENVIRONMENT & MINING
SEAM
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ABSTRACT

Numbers of roots present per unit area of soil and the individual root tensile strength for two varieties of Douglas-fir--Coast fir (Psuedotsuga menziesii) in western Oregon and Rocky Mountain fir (var. glauca) in central Idaho decreased rapidly with time after felling. Seventy-five percent of the Douglas-fir roots 1 cm or smaller in diameter were lost within 24 months after felling in the coastal variety, and within 60 months after felling in the Rocky Mountain variety.

Numbers of roots per unit area of soil were combined with tensile strength of iadividual roots to estimate total tensile strength per unit area of soil. Total tensile strength declined from about 1,700 kg/m^2 to about 230 kg/m^2 within the first 30 months after felling for roots 1 cm and smaller of the Coast Douglas-fir. Total tensile strength declined from about 850 kg/m^2 to about 300 kg/m^2 for the same time period and root size class of the Rocky Mountain Douglas-fir. Coast Douglas-fir roots are stronger than those of the Rocky Mountain variety, but decay faster. Live strength is a characteristic of the variety of fir, but differences in decay rates are probably a function of climate.

INTRODUCTION

The role of tree root strength in the stability of slopes has been the subject of speculation and experimentation for several years. There is an increasing need to understand the effect of tree root strength on slope stability wherever land with a high potential for slope failure provides valuable timber and water resources. Land managers must have quantitative data on the effects of timber removal upon slope stability to make decisions as to where, how much, and by what method timber may be safely harvested from areas where landslides are common.

This study originated as a result of the concern by the Bureau of Land Management (BLM) in western Oregon over timber harvesting on shallow soils having a high potential for landslides. The lands support old-growth timber stands of up to 80,000 board feet per acre, with Coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) the principal commercial species. In addition, all of the larger streams support anadromous fish. The primary objective of the BLM field study was to identify areas with a high potential for slope failure by debris avalanches and flows by measuring the five major stability factors: slope gradient, soil depth, pore water pressure, soil shear strength, and root strength. A secondary objective was to determine how many trees could be safely removed from certain sites without causing slope failures through loss of root strength.

The study was initially limited to certain portions of western Oregon. However, in other parts of the Rocky Mountains where debris avalanches and flows are also common, Douglas-fir root systems may also influence slope stability. The question then arose whether the roots of the Rocky Mountain variety of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) were as strong as the coastal variety. Therefore, the study of Douglas-fir root systems was expanded to include the root strength of Douglas-fir in the mountains of central Idaho.

This report describes and compares the decrease in numbers of roots and the decline in tensile strength of individual roots with time after felling, for two varieties of Douglas-fir. These data are then combined to describe the decline of root strength in terms of force per unit area. Finally, results are compared against observations of unstable slopes, and the role of roots in slope stability is discussed.

Work in progress is aimed at developing and testing criteria and equations for applying root strength in analyses of slope stability. This work will be the subject of future reports.

STUDY AREAS

That portion of western Oregon judged to have a high frequency of debris avalanche and flows contains about 606,036 hectares (2,340 square miles). This area is underlain by the Tyee and Yamhill Formations (Wells and Peck 1961) as shown in figure 1. Much of the western portion of these lands is composed of steep, highly dissected slopes, with shallow, loamy-skeletal soils. A heavy winter rainfall interacts with these factors to create a high potential for debris avalanches and debris flows.

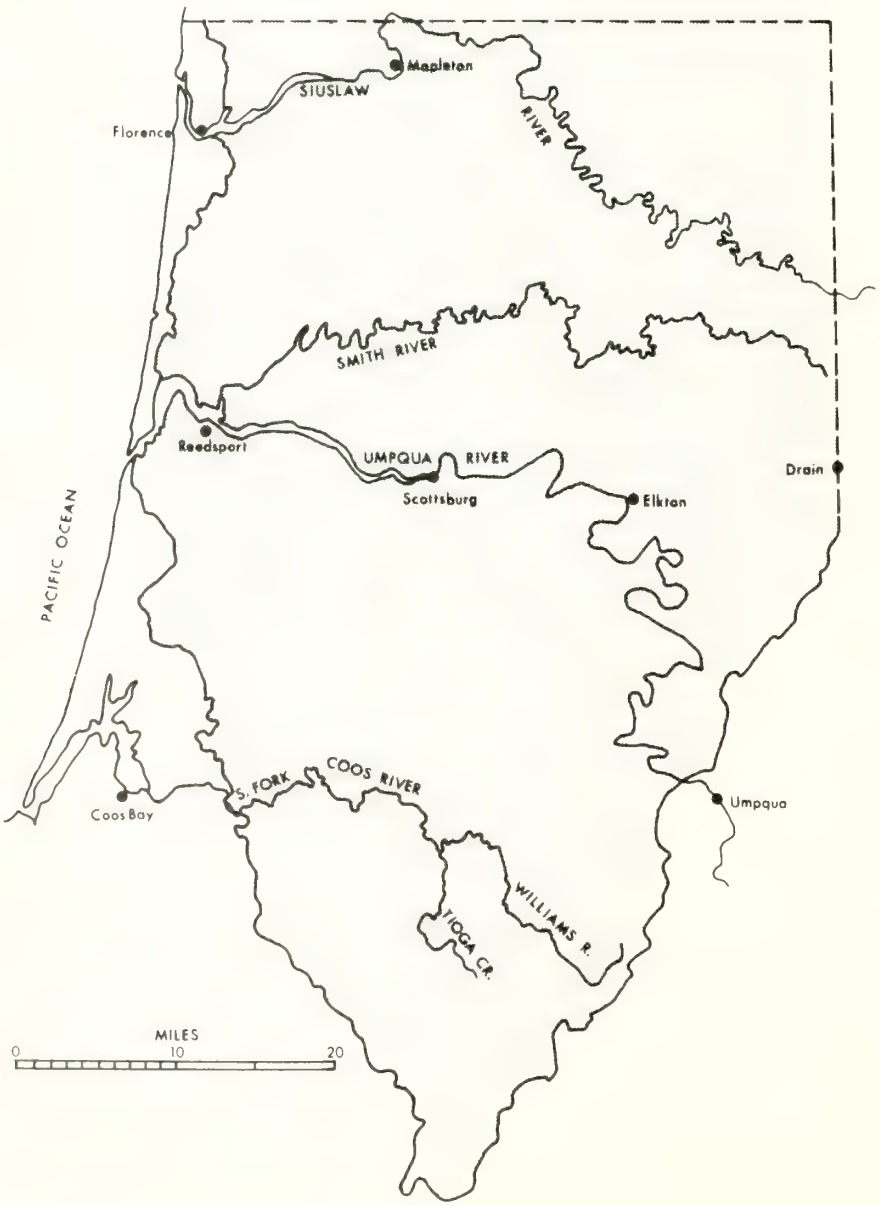

Figure 1. The western Oregon study area (adapted from Wells and Peck 1961). Shading indicates lands with high potential for debris avalanches and flows.

The geologic material is mainly sandstone of the Tyee Formation described (Bell and Peck 1961) as:

> ...rhythmically bedded feldspathic and micaceous massive-bedded sandstone and subordinate siltstone.... Each bed is graded, ranging from coarse sandstone at the base to fine sandstone and siltstone above...

The Yamhill Formation is similar to the underlying Tyee Formation, with massive-bedded sandstone and siltstone and shale interbeds. The relatively hard sandstone of both formations may form cliffs, and also may form slopes from 65 to more than 120 percent leading away from concave headwalls on narrow ridges. The underlying sandstone may be hard and relatively smooth and massive, or it may be well fractured. Thick beds of siltstone form more moderate slopes of 45 to 70 percent.

Soils range in depth from less than 25 cm (10 in) over hard sandstone to 4 m (13 ft) in deep colluvial deposits in channel bottoms and in pockets where the bedrock is deeply weathered. Table 1 lists some characteristics of the soil series commonly found in the most slide-prone portions of western Oregon, as described by Townsend and others (in press).

Table 1.--

Soil types or land types	Coarse fragment content (% by vol.)	Depth to bedrock	Underlying geologic material
OREGON			
Umpcoos			
Very gravelly sandy loam	> 35	25 to 50 cm	Hard, massive, sandstone
Jason			
Gravelly loam	35	25 to 50 cm	Soft or fractured sandstone and siltstone
Digger			
Gravelly loam	> 35	0.5 to 1.0 m	Sandstone and siltstone
Bohannon			
Gravelly clay loam	35	0.5 to 1.0 m	Sandstone and siltstone
Slickrock			
Gravelly loam	35	1.0 to 1.5 m	Weathered sandstone or siltstone
IDAHO			
F4			
Loams	variable	25 cm to 1 m	Weathered granite
F5			
Sandy loams	variable	25 cm to 1 m	Hard to well weathered granitic granite

The Idaho study site was located on the Boise National Forest along the South For of the Payette River near Lowman in the southern part of the Idaho Batholith (fig.2). This part of the Batholith is made up of a granodiorite, that may range from massive, practically unweathered rock to a highly fractured, highly weathered material. Soil also varies with depth ranging from 50 cm to 1 m (table 1). Soil textures are generally coarse and single-grained, with a clay plus silt content of from 5 to 15 percent (Megahan 1969).

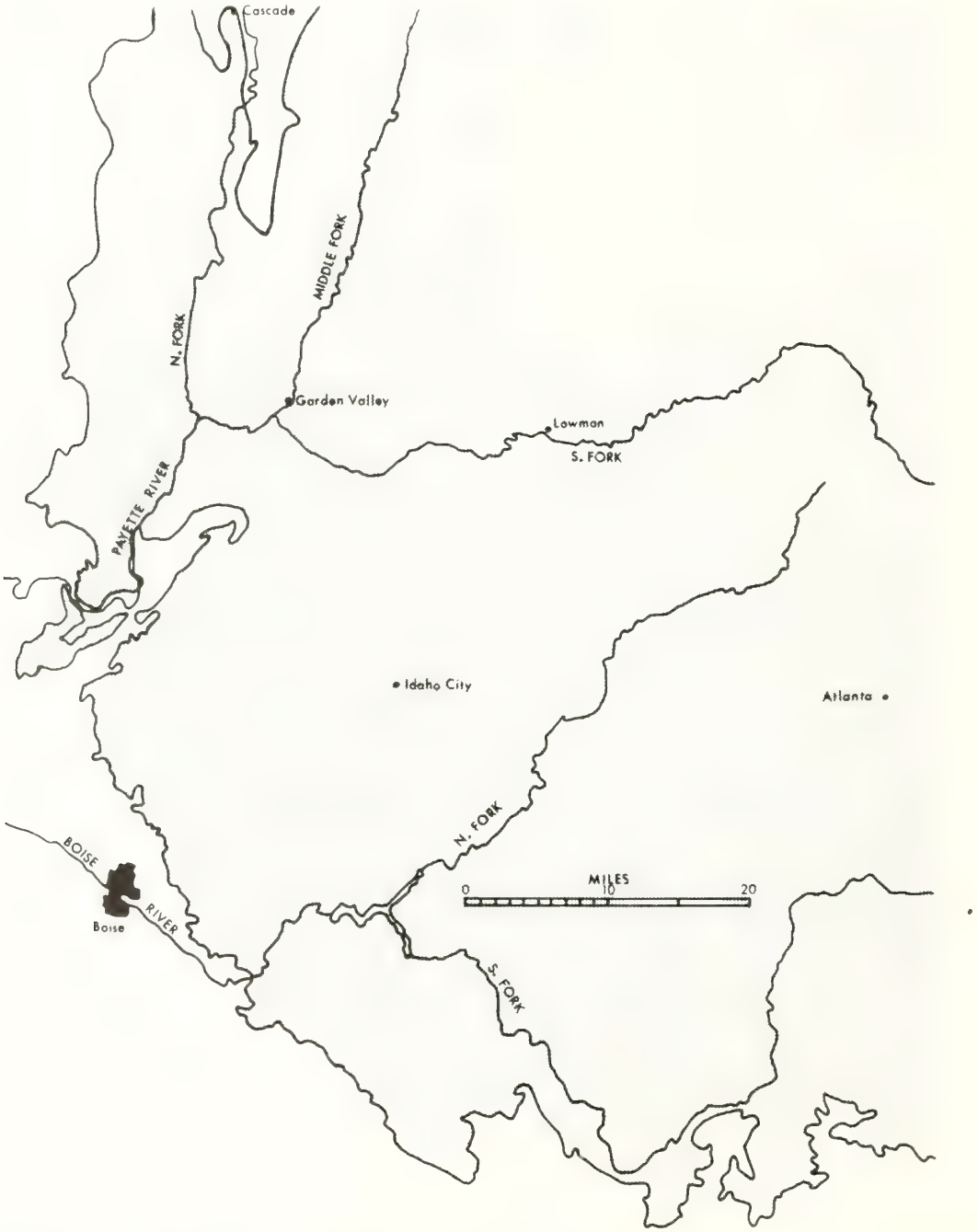

Figure 2.--The central Idaho study area (adapted from Ross and Forrester 1959). Shading indicates lands with high potential for debris avalanches and flows.

Most of the precipitation in the southern Batholith occurs as snow, which reaches maximum accumulation between March 1 and April 15. Large, long-duration Pacific storms may occur in the winter, and these storms often cause flooding as a result of rain and accelerated snowmelt. Mass erosion in the Idaho Batholith is most often the result of rain or rain-augmented snowmelt from October 15 to April 15 (Megahan 1969). For example, a survey of just one district of the Payette National Forest, following intense rain and snow in December 1964, showed more than 400 mass failures. A large natural burn of about 600 acres that occurred 3 to 4 years before was the source of 45 percent of these failures, while undisturbed forest had only 5 percent. Stream channels suffered 30 percent, and roads 20 percent of the total number of failures (Megahan 1969). The relatively high percentage of mass failures that occurred on the burned-over area indicates that declining root strength following death of trees may be an important factor in mass failure of shallow soils on steep slopes in the Idaho Batholith.

The F4 and F5 land types contain major habitat types in the Douglas-fir series, with minor habitat types in the ponderosa pine and subalpine fir series. Samples for measuring characteristics of root systems were taken from the Douglas-fir/ninebark (*Pseudotsuga menziessi* var. *glauca-Physocarpus malvaceus*) habitat type. Both land types are rated as having high mass failure potential (Wendt and others 1975).

OTHER STUDIES RELATING TREE ROOTS TO SLOPE STABILITY

Investigators have recognized the correlation between timber cutting and increased frequency of landslides with time after logging. Most notable was the paper by Bishop and Stevens (1964), who wrote that the number and acreage of slides in southeast Alaska increased more than 4.5 times within 10 years after logging. They attributed the increasing frequency of landslides following logging to root deterioration, which requires several years to exert its full impact on slope stability.

Nakano (1971), reporting on the results of research in Japan, showed that the resistance of stumps to uprooting decreased with years after cutting. The decreasing root strength on a unit area basis was offset by increasing resistance to uprooting of the young trees growing on the site. The net result of timber cutting was an increasing frequency of landslides, expressed as a percentage of land area, until about 16 years after cutting. From there on, the increasing root strength of the young growing stand reduced the frequency of landslides to the preharvest level.

Actual measurements of the decrease in tree root strength following cutting are not commonly found in the literature. Swanston (1969) mentions that Alaskan measurements of shear strength perpendicular to the grain of lateral roots greater than 1 inch in diameter showed a very gradual decrease in strength with time after cutting. Decay was not evident in roots from stumps less than 4 years old, but was almost always found in roots from stumps older than 4 years.

O'Loughlin (1974) studied landslides in southern British Columbia and found that a high percentage of roots of all sizes along the margins of landslides failed in tension, while a smaller percentage failed in shear. O'Loughlin's work was concerned mainly with determining the rate at which the tensile strength of Douglas-fir and western redcedar roots decreased with time after cutting. His results showed that the tensile strength of Douglas-fir roots decreased by more than one-half within 3 years after cutting. Cedar roots required 5 years to lose one-half of their tensile strength. O'Loughlin's data did not include changes in the numbers of roots by size classes with years after cutting. He alluded to this phenomenon by mentioning "...that the roots taken from older stumps were larger than roots sampled from younger stumps..." He noted that old cedar stumps in an area clearcut in the 1930's retained roots with diameters greater than about 15 cm, and that the smaller roots had decayed and disappeared probably years before. He also measured the diameters of 150 broken roots from the soil below 45 cm in the headscarps of three landslides. The mean of these diameters (whether inside or outside bark was not stated) was 1.07 cm. He concludes that "small roots constitute a major part of the root network in the lower B horizon of the stony mountain soils." This points out that it is important to measure the change in the numbers of roots, particularly the smaller sizes, with time after cutting as well as to measure the declining tensile strength of roots.

The question remains as to how to apply quantitative data to equations used in analyzing slope stability once the decay function of root systems is understood. A Japanese study (Endo and Tsuruta 1969) measured the increase in soil shear strength by making large-scale direct shear tests on soil pedestals containing live tree roots. The soil shear strength increased directly with the bulk weight of roots per unit volume of soil. Their results showed that data on the shear strength of soil with live roots fit the equation, $S = \alpha + \beta R + \sigma \tan \phi$; where

S = total shear strength in kg/m^2
α and β = empirical constants
R = weight of roots in g/m^3
σ = normal stress in kg/m^2
ϕ = angle of internal friction of the soil.

Note that tree root strength is considered to be a cohesive force. Swanston (1970) made a stability analysis of three landslides in cohesionless soils in southeastern Alaska and found that an "apparent cohesion" of 69 to 89 pounds per square foot was needed to maintain stability. He concluded that the most likely source for this stabilizing force was the anchoring effect of tree roots growing through the slide-prone, weathered till into the compacted till. Swanston and Dyrness (1973) considered roots to "provide continuous long-fiber cohesive binders to the soil mass proper and across local zones of weakness within the soil mass." In their opinion, the anchoring effect of roots can be extremely important on some steep, shallow soils of the western United States.

STUDY METHODS

Samples of tree roots were taken from locations within old-growth (100 to 200 years), Douglas-fir sites in uncut stands and unburned cutover areas. The ages of the cutover areas ranged from 2 to 111 months for the Oregon sites, and 2 to 144 months for the Idaho sites. The ages of cutover areas were determined by consulting records, foresters, and contract administrators. One representative tree or stump in each location was selected as the center of a plot. The slope gradient of the site and the location and diameters of all neighboring trees or stumps were measured by tape, abney level, and compass. A pit for root sampling was located halfway between the center of the plot and one of the neighboring trees or stumps. Criteria for the location of a pit were: trees or stumps were to be Douglas-fir; avoid patches of woody shrubs such as vine maple (*Acer circinatum*); and avoid immovable piles of logging debris.

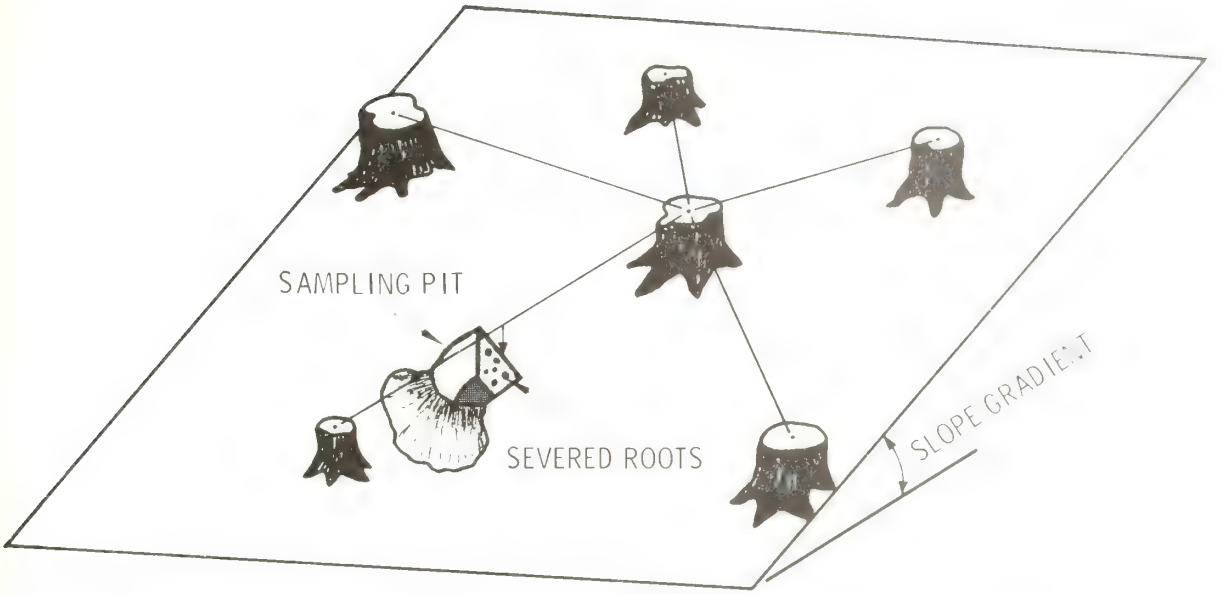

Figure 3.--Central stump of sampling site connected to neighboring trees by rays.

Each pit was dug 1 m wide and to a depth of 1 m or to bedrock, whichever was shallower. The face of the pit was located at the center of and at right angles to the ray connecting the center of the plot and the neighboring tree or stump (fig. 3). Root samples for testing of tensile strength were collected as the pit was excavated. Living Douglas-fir roots of both varieties have a distinctive, crimson-colored inner bark, which made them easy to identify. The bright color darkened to a brownish red in dead Douglas-fir roots, which was still distinctive. The diameter, inside bark, of each Douglas-fir root found in the pit face was measured and recorded. The sizes of these roots ranged from 0.4 mm (0.016 in) up to about 10 cm (4 in). Root samples were stored temporarily in a 50 percent solution of isopropyl alcohol until they could be transported to the lab and stored in a solution of eight parts alcohol and one part formaldehyde. The alcohol-formaldehyde solution was used to kill any micro-organisms that could continue the decay of roots during storage.

A device was designed and constructed to measure the tensile strength of tree roots, using hydraulic pressure to hold the ends of the sample.[1] Another hydraulic cylinder applied a tensile force to cause failure, and a dynamometer measured the tensile force at failure. Roots up to 14.3 mm (0.56 in) in diameter could be tested. The capacity of the device was limited only by the holding ability of the hydraulically operated grippers and the 1,000-lb capacity of the dynamometer. The tensile tests were not strain controlled. Each root (saturated from the alcohol-formaldehyde solution) had the bark carefully stripped, the ends secured in the tensile tester, and tensile force applied. The maximum tensile force at failure was recorded by the "lazy hand" on the dynamometer. The average diameter of the root at the break was measured and recorded along with any notes on obvious decay, high resin content, and bends or crooks which may have affected the tensile strength. All roots were tested as long as the ends of the sample were straight enough to fit in the tester and the sample was not too decayed to prepare for testing. More than 90 percent of the roots broke outside of the end clamps. Test results for those roots which failed within the end clamps were discarded.

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[1]The authors are indebted to Bland Z. Richardson of the Forest Service, Intermountain Forest and Range Experiment Station, for designing and supervising the construction of this instrument. A publication describing this device in detail is in preparation.

RESULTS

Numbers of Roots Per Unit Area of Soil

Analysis of measurements of the numbers of roots present in the soil with time after felling of the stand showed distinct differences between Coast and Rocky Mountain Douglas-fir. Plots of these data showed that the decline in numbers of Coast Douglas-fir roots followed a distinctive curve--concave upwards with a steeply climbing left limb and a gradually declining right limb. The curve expressing the prediction equation, as shown in figure 4, was developed using the techniques of Jensen and Homeyer (1970) and Jensen (1973). The appendix presents curves fitted to raw data.

The Rocky Mountain Douglas-fir showed a less rapid decline in numbers with time according to the semilogarithmic model: $N = a + b \log_{10} (\text{Time} + 1)$. The constant 1 was added to the time after felling in months to allow the logarithmic transformation of data from live roots, where the time after felling is zero. Figure 5 shows the predicted numbers of roots with time after felling; figure 6 presents the parameters and equations for both varieties of Douglas-fir. (Curves are fitted to raw data in the appendix.)

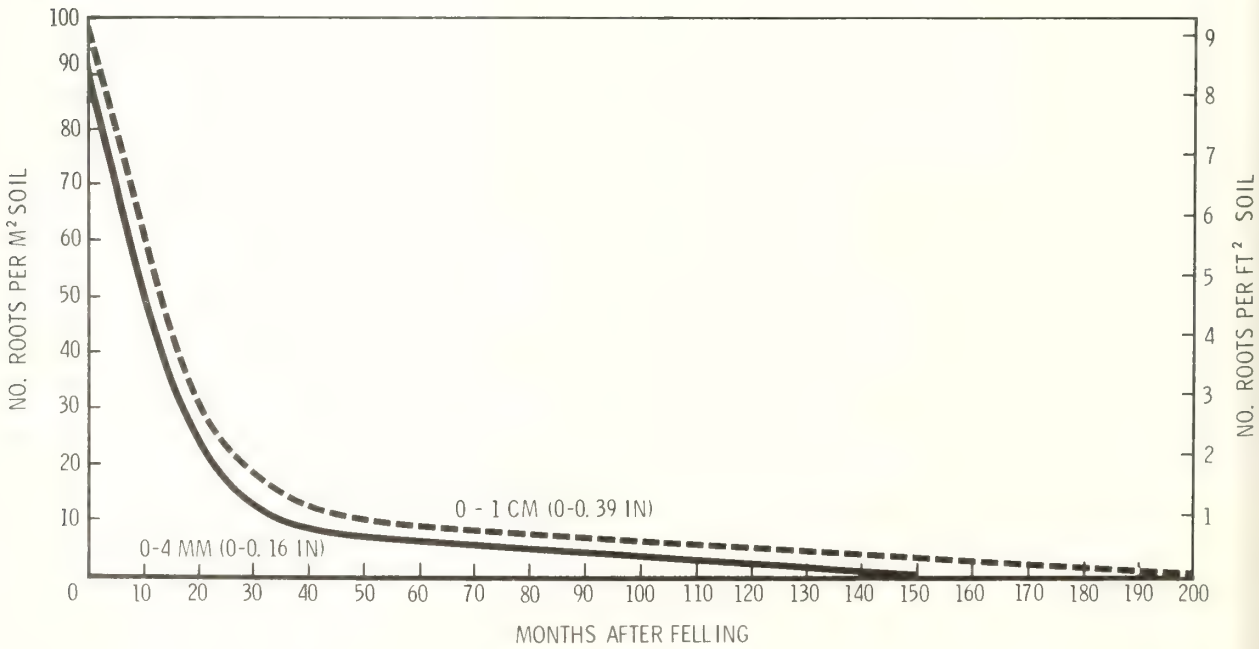

Figure 4.--Decline in numbers of Coast Douglas-fir roots per unit area of soil.

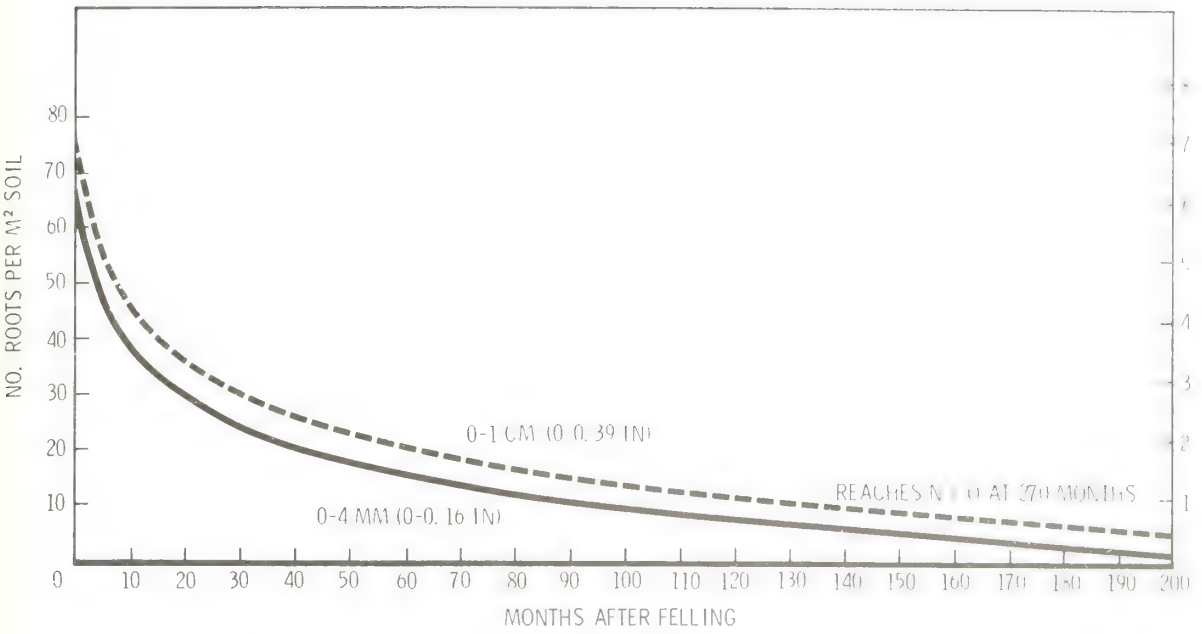

Figure [illegible]--[illegible] for numbers of [illegible] roots per [illegible] with time after felling.

Coast Douglas-fir: $N = a \cdot e^{-\left|\frac{b - \text{Time}}{c \cdot d}\right|^{f}} + (1 - \frac{\text{Time}}{b})^{g}$

where: N = numbers of roots per unit area of soil, Time = months following felling (live roots have time = 0); range = 0 to 111 months.

Units	Diameter size class	a	b	c	d	f	g	[illegible]	[illegible]	Months	Months
N/m	0 to 4 mm	247.4	130	250	0.39	5	10.9	0.86	15.03	184	[illegible]	36.6
N/f	0 to 0.16 in	23.0	130	250	[illegible]	5	1.01	0.86	1.21	184	2.8	36.6
N/m	0 to 10 mm	232.2	200	250	0.20	2.7	12.9	0.89	11.66	[illegible]	34.5	36.6
N/f	0 to 0.39 in	21.6	200	250	0.20	[illegible]	1.20	0.89	1.08	[illegible]	3.2	36.6

Rocky Mountain Douglas-fir: $N = a + b \log_{[illegible]}(\text{Time} + 1)$

where: N = numbers of roots per unit area of soil; Time = months following felling (live roots have time = 0); range = 0 to 114 months.

Units	Diameter size class	a	b	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Months	Months
N/m	0 to 4 mm	69.2	[illegible]	0.96	5.20	2.77	1.71	[illegible]	26.4	54.6
N/f	0 to 0.16 in	[illegible]	[illegible]	[illegible]	0.48	0.26	0.16	[illegible]	[illegible]	54.6
N/m	0 to 10 mm	77.2	[illegible]	[illegible]	6.90	3.68	2.27	191	32.0	54.6
N/f	0 to 0.39 in	7.2	[illegible]	0.93	[illegible]	0.34	0.21	194	2.9	54.6

[1/] All F values are highly significant at the [illegible] percent level.

Figure 6.--Statistics and equations for estimating the numbers of roots per unit area of soil with time after felling for Coast and Rocky Mountain Douglas-fir.

Time after felling was the only independent variable used in this analysis. Information on tree spacing and tree diameter is expected to affect the numbers of roots per unit area of soil, but these data will be reserved for future analyses.

Figures 4 and 5 show that the Coast Douglas-fir has a greater number of live roots per square meter of soil in all size classes and has a faster decline in numbers with time after felling than the Rocky Mountain Douglas-fir. It can be seen that the Rocky Mountain Douglas-fir roots in a given size class remain intact about 35 percent longer than Coast Douglas-fir roots when the curves are extended to the horizontal axis of figures 4 and 5. These estimations of the time required for the numbers of roots 0 to 1 cm in diameter to reach zero is a minor extrapolation from the data for Coast Douglas fir and a major extrapolation for the Rocky Mountain variety. It is speculative how much of this difference in durability is caused by differences in the wood and how much is caused by differences in climate and the activity of micro-organisms.

The remaining roots larger than 1 cm (0.39 inch) were subdivided into size classes and analyzed to see if there was a trend in numbers with time by comparing the slope of a regression line for each class with zero. We would expect that the numbers of these roots would eventually reach zero. However, the results of these tests showed that the numbers of roots in the larger size classes remained constant with time over the range in time used in this study. Table 2 presents the mean value of the number of roots per unit area of soil for each size class and the mean diameter of the roots in each size class.

Table 2.--*Mean numbers of Coast and Rocky Mountain Douglas-fir roots per unit area of soil for the larger size classes*

Size class	Mean diameter	Number/meter^2	Number/foot^2
		COAST DOUGLAS-FIR	
1 to 2 cm	1.46 cm	1.59	--
0.39 to 0.78 in	.72 in	--	0.147
2.1 to 4 cm	2.78 cm	.409	--
0.79 to 1.59 in	.90 in	--	.0380
4.1 to 6 cm	4.54 cm	.106	--
1.60 to 2.38 in	2.23 in	--	.00987
6.1 to 8 cm	6.46 cm	.104	--
2.39 to 3.17 in	2.67 in	--	.00971
		ROCKY MOUNTAIN DOUGLAS-FIR	
1 to 2 cm	1.36 cm	1.92	--
0.39 to 0.78 in	.68 in	--	.178
2.1 to 4 cm	2.86 cm	.922	--
0.79 to 1.59 in	1.36 in	--	.0857
4.1 to 6 cm	5.15 cm	.111	--
1.60 to 2.38 in	2.00 in	--	.0103
6.1 to 8 cm	6.39 cm	.0584	--
2.39 to 3.17 in	2.52 in	--	.00543

The greatest source of error in the data on the decline in numbers of roots with time is the determination of the correct date of felling. Errors in dating the cut have their greatest effect on samples from the younger clear-felled areas because of the rapid initial decline in numbers. Fortunately, the younger cuts are the easiest to date accurately because of the availability of records and personnel who administered the sale. An error in dating of as much as 6 months would have relatively little effect on root samples from an area cut 10 years ago.

Tensile Strength of Individual Roots

Tensile strength of roots was plotted against diameter (inside bark) by time after felling, and these results showed distinct differences in the rate of decline of strength with time after felling for the two varieties of Douglas-fir. The model for root tensile strength was nonlinear for each variety, with strength a function of diameter raised to an exponent which is a function of time after felling. The models and their statistics are shown in figure 7.

Figure 8 shows that predicted root tensile strength of Coast Douglas-fir for various times after felling. The strength of a 1 cm root drops from 341 to 175 kg at 12 months after felling--a loss of 49 percent in 1 year. By 48 months after felling, a 1 cm root has lost 74 percent of its live strength.

COAST DOUGLAS-FIR

$$\text{Tensile Strength} = a\,(b \cdot \text{Diameter})^{(1.8\ -\ 0.06\sqrt{\text{Time}})}$$

where: Time = months after felling (live roots have time = 0).

Strength units	Diameter units	a	b	r	Sy·x	F[1/]
Kilograms	Millimeters	1.04	2.516	0.804	19.2	885
Pounds	Inches	2.30	0.0156	0.804	42.3	885

ROCKY MOUNTAIN DOUGLAS-FIR

$$\text{Tensile Strength} = (a - b \cdot \text{Time})\,(c \cdot \text{Diameter})^{(1.676\ -\ 0.0004 \cdot \text{Time})}$$

where: Time = months after felling (live roots have time = 0).

Strength units	Diameter units	a	b	c	r^2	Sy·x	F[1/]
Kilograms	Millimeters	180.2	0.381	0.0786	0.802	20.4	456
Pounds	Inches	397.3	0.840	0.000489	0.802	44.9	456

[1/] All F values are highly significant at the 99 percent level.

Figure .--[illegible] of Douglas-fir.

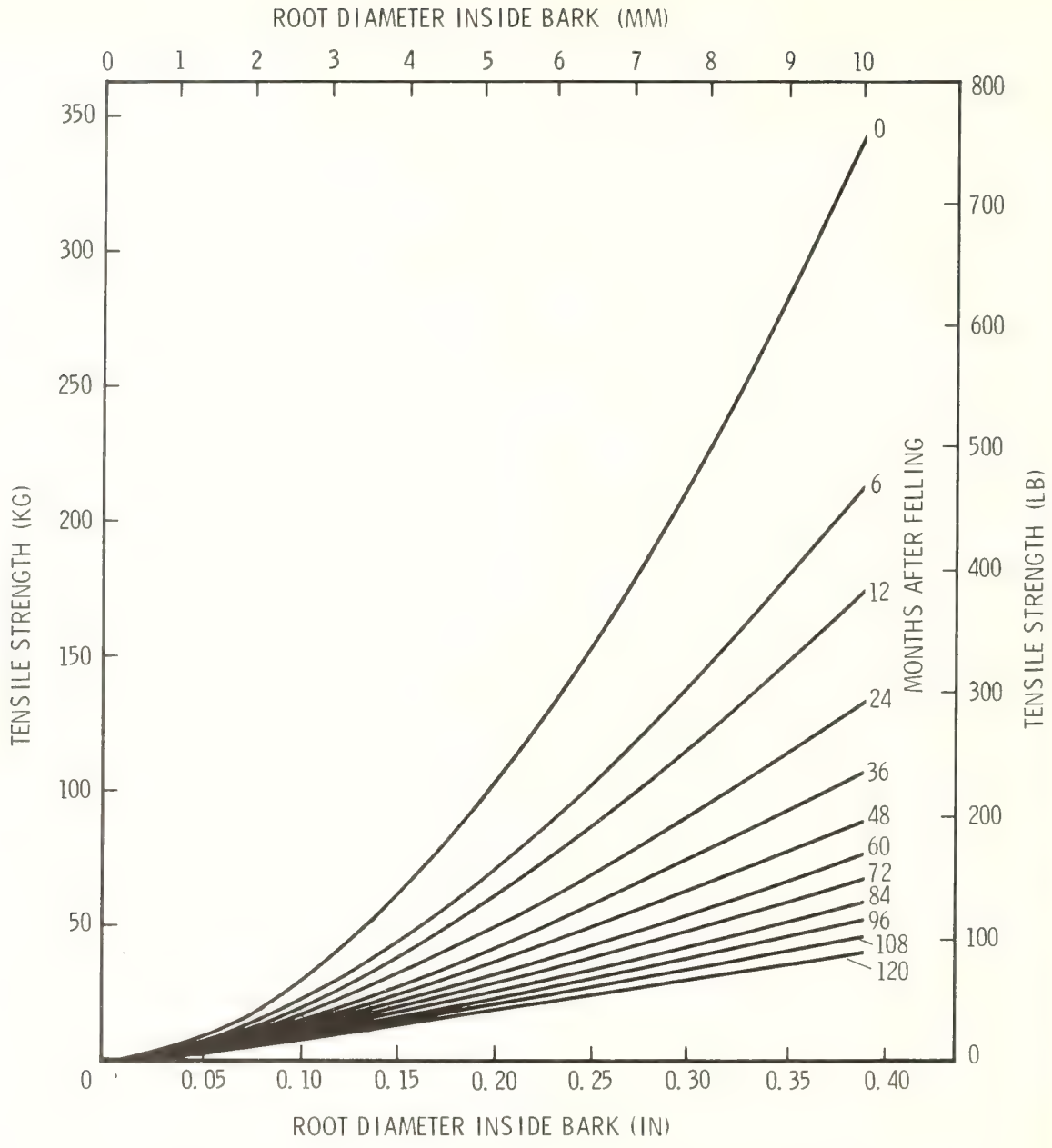

Figure 8.--Individual root tensile strength for Coast Douglas-fir.

The Rocky Mountain variety proved to have relatively weak roots with a slow, gradual decline in strength with time after felling. Figure 9 shows the predicted root tensile strength by diameter and time after felling (note the change in scale from fig. 8 to fig. 9). A 1 cm root loses only 30 percent of its fresh tensile strength after 144 months.

A comparison of these two figures illustrates the difference in root strength and its decline with time after felling for the two varieties of Douglas-fir. A 1 cm root of Rocky Mountain Douglas-fir has only 35 percent of the strength of Coast Douglas-fir when fresh, but is about 2.2 times as strong after 120 months.

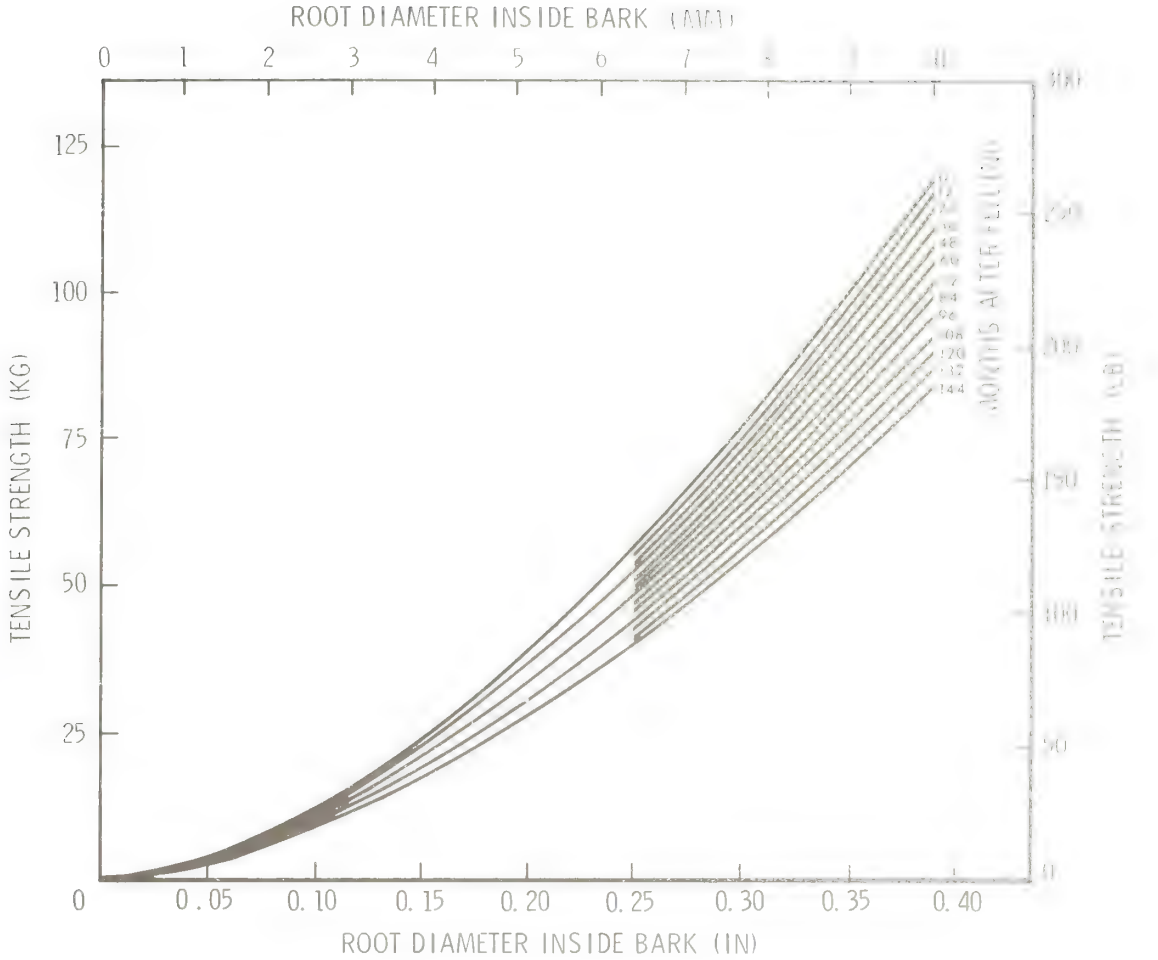

Figure 9.--Predicted [illegible]

The prediction equation for Coast Douglas-fir (fig. [illegible]) was applied to the results of laboratory tensile tests on Coast Douglas-fir from British Columbia in a publication by O'Loughlin (1974). Figure 10 shows O'Loughlin's plotted data for live roots, with the predicted curve from this study superimposed. The relatively good fit of this curve indicates that the tensile strength of live Coast Douglas-fir roots does not vary from Oregon to British Columbia.

O'Loughlin's data show much less scatter than data developed during this study. O'Loughlin selected straight, uniform sections of roots for his laboratory tests, which reduces the variance of the test results. In the present study, all roots were tested regardless of crooks, resinous portions, or advanced decay. This increases the variance of the results, but it also gives an estimate of the variation that may be expected in the natural populations.

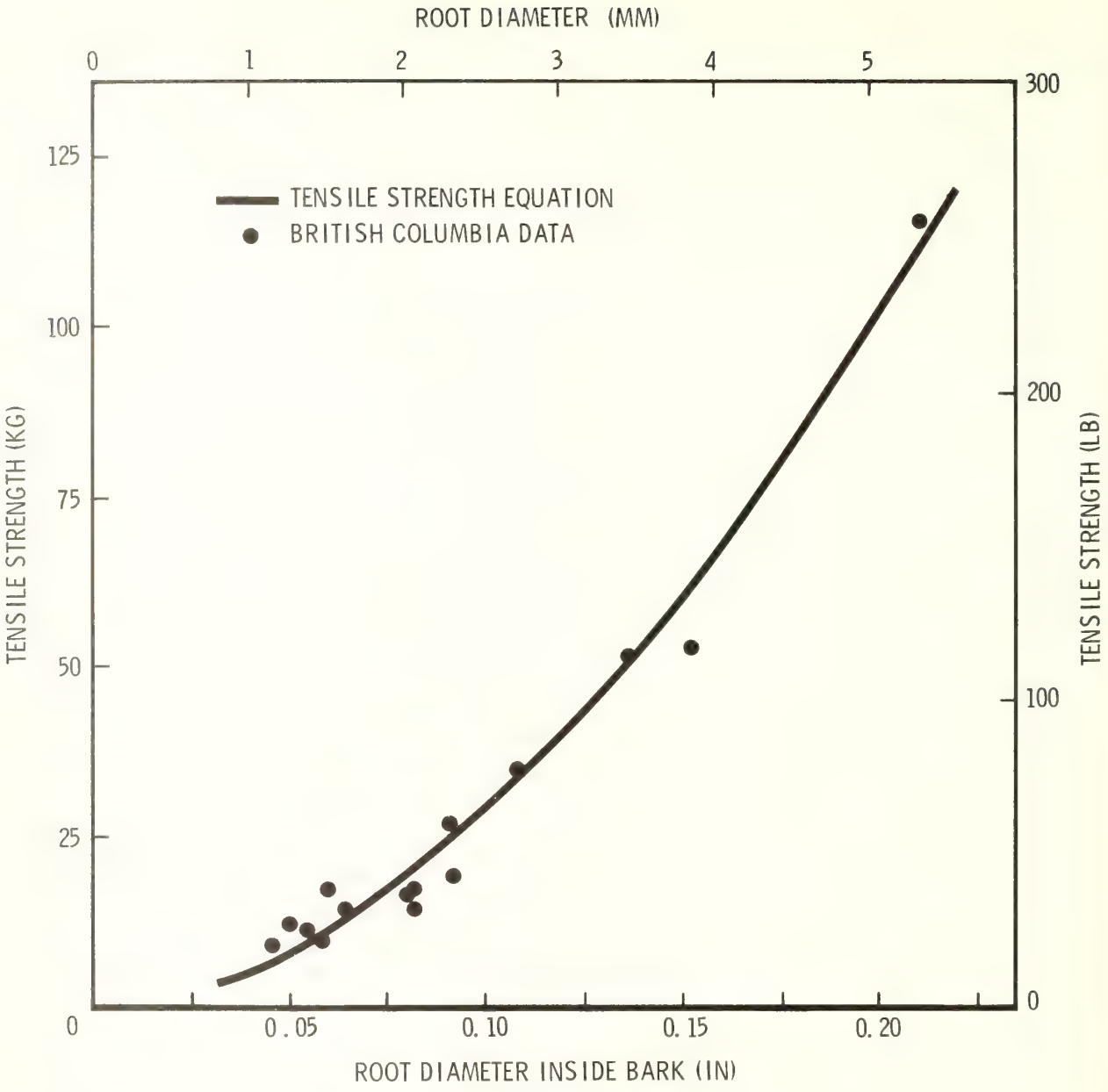

Figure 10.--Application of the tensile strength equation to British Columbia data for live roots.

Root Tensile Strength Per Unit Area of Soil

The next step in the analysis was to combine the numbers of roots per unit area of soil and the individual root tensile strengths to estimate the total root tensile strength per unit area of soil. This was done by summing the product of the number of roots of each diameter in a sample pit and the estimated tensile strength for each diameter. This process formed a data set of tensile root strength per unit area of soil based on samples from live stands and from areas felled up to 144 months before. It should be emphasized that these data represent the maximum root tensile strength per unit area of soil in a vertical plane oriented as a perpendicular bisector to a ray connecting two trees or stumps (fig. 3).

General Model: $\frac{\text{Tensile Strength}}{\text{Unit Area of Soil}} = a \cdot e^{-\left|\frac{b - \text{Time}}{c} - 1\right|^{f}}$

where: Time = months after felling (live sites have time = 0).

Strength units	Root size class	a	b	c	d	f				
					COAST DOUGLAS-FIR					
Kg/m^2	0 to 1 cm	2840	200	300	0.36	6.0	1.02	0.826	229.6	71.3
$\#/ft^2$	0 to 0.39 in	592.0	200	300	.36	6.0	.208	.826	47.05	
Kg/m^2	0 to 4 mm	1435	120	300	.60	7.0	1.59	.913	77.0	156.9
$\#/ft^2$	0 to 0.16 in	294.1	120	300	.60	7.0	.326	.913	15.8	
					ROCKY MOUNTAIN DOUGLAS-FIR					
Kg/m^2	0 to 1 cm	1134	430	475	.10	5.0	.770	.709	112.2	19.6
$\#/ft^2$	0 to 0.39 in	232.5	430	475	.10	5.0	.158	.709	23.0	19.6
Kg/m^2	0 to 4 mm	322.1	155	180	.15	3.5	1.012	.836	42.8	76.3
$\#/ft^2$	0 to 0.16 in	65.98	155	180	.15	3.5	.207	.836	8.77	76.3

[1/] The distribution will be assumed to be normal until otherwise established. The propriety of the Sy·x and F estimators is contingent upon this assumption.

Figure 11.--Models for predicting total root tensile strength per unit area of soil by time after felling. (Total root strength per unit area of soil was developed using actual numbers of roots per unit area and the estimated individual root tensile strength.)

One-half of the data for each variety of Douglas-fir were selected at random and used to develop the curve form for the decline in tensile strength with time after felling, while the remaining data were used to test the accuracy of the curve fitted to each set of data. The models and their statistics are shown in figure 11. The appendix presents plots of the raw data and the fitted curves.

Figure 12 shows the decline in total root tensile strength per unit area of soil for Coast Douglas-fir for two size classes; figure 13 provides this information for the Rocky Mountain variety. Plots of the data reserved for curve-form development indicated that the form of the relationship would be reasonably approximated by a combination of a concave upward curve sloping steeply to the left and a linear segment sloping gently to the right. These curves were fitted by the methods outlined by Jensen (1973).

Time after felling was the only independent variable used in this analysis. Tree spacing and tree size is expected to affect the numbers of roots per unit area of soil and thereby also affect the tensile strength per unit area of soil. These data have been reserved for future analyses.

A comparison of figures 12 and 13 shows that for the 0 to 1 cm size class, the Coast Douglas-fir at time zero has nearly twice the strength of the Rocky Mountain Douglas-fir. The strength values are about equal 30 months after felling, and by 144 months, the Rocky Mountain Douglas-fir has about 3.6 times the strength per unit area of soil as the Coast Douglas-fir.

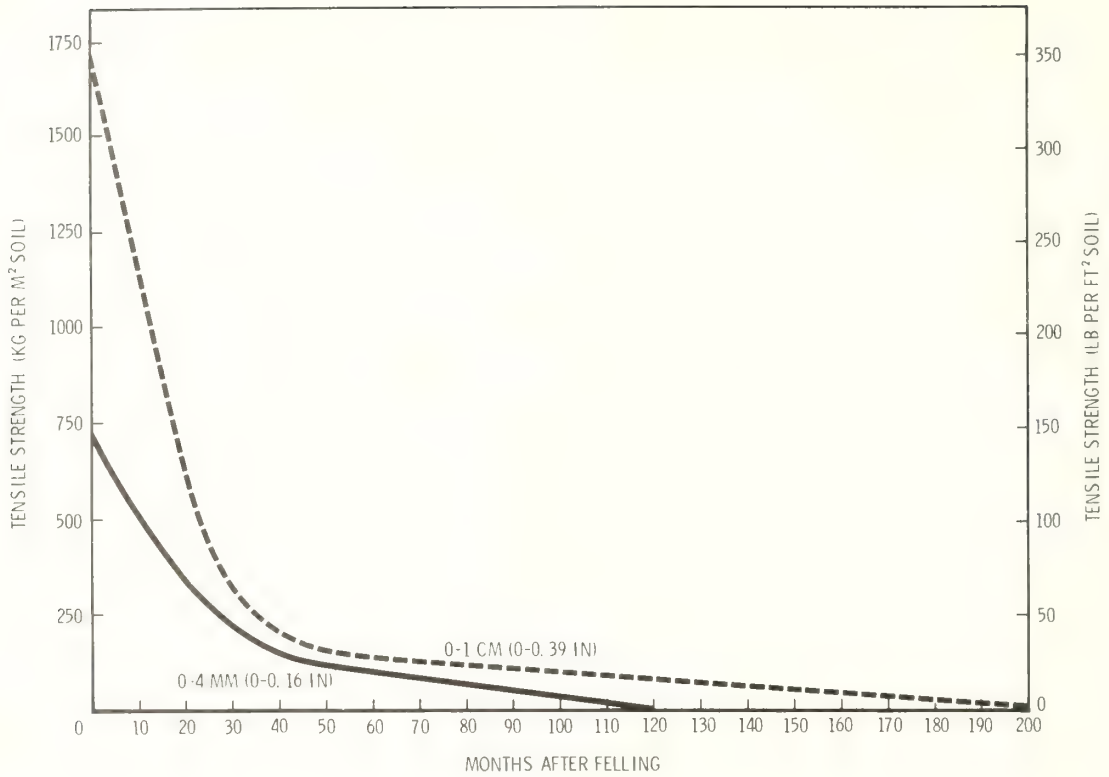

Figure 12.--Root tensile strength per unit area of soil for Coast Douglas-fir.

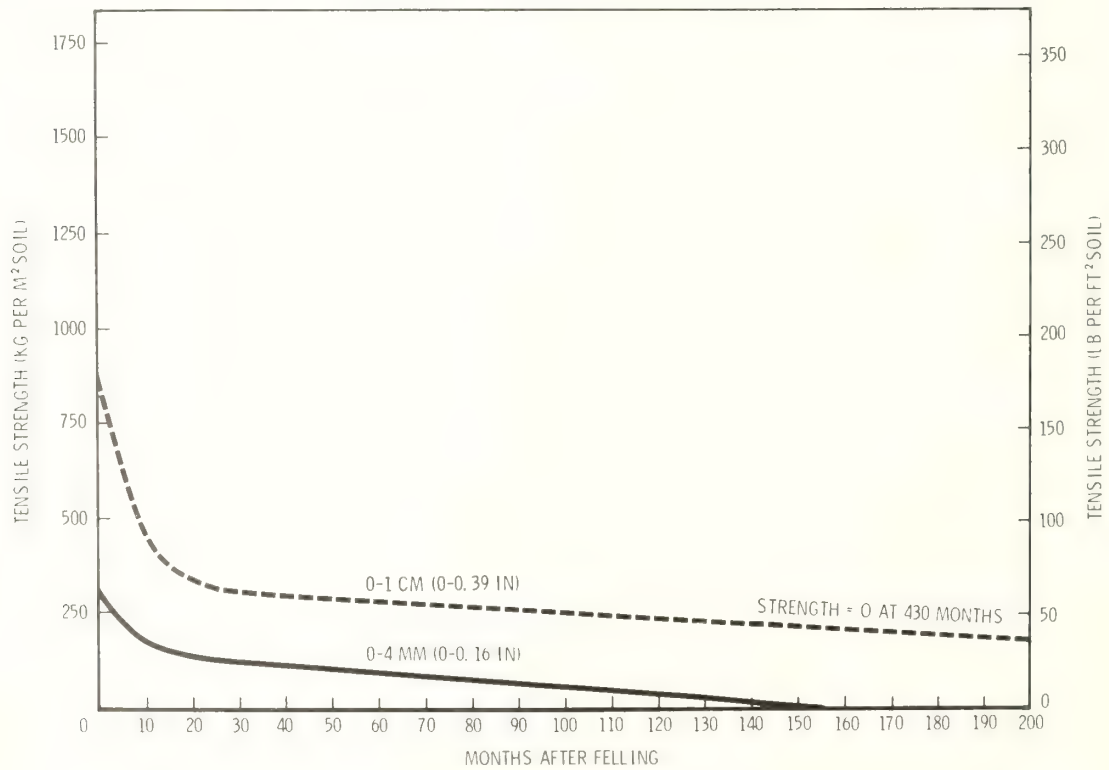
TENSILE STRENGTH (KG PER M² SOIL)
TENSILE STRENGTH (LB PER FT² SOIL)
0-1 CM (0-0.39 IN)
STRENGTH = 0 AT 430 MONTHS
0-4 MM (0-0.16 IN)
MONTHS AFTER FELLING

Figure 13.--Root tensile strength per unit area of soil for Rocky Mountain Douglas-fir.

DISCUSSION

From the observations and measurements made during this study, a concept was developed to explain how the change in numbers and strength of tree roots after felling affects slope stability. The presence of Douglas-fir roots in pits dug halfway between trees in living stands supports the idea that living tree roots form a reinforcing network in the soil. The finer roots (1 cm and smaller) are found throughout the rooting zone of each tree's root system. It is at the lateral edges of the root mass and across the bottom of the root system that the fine roots have their greatest effect on slope stability.

There are three important ways in which these fine roots increase the shear strength of the soil mass. First, these roots provide tensile reinforcement to the soil mass enclosed within the rooting zone of an individual tree. This effect may be observed on windthrown trees where the entire soil-root mass overturns as a single unit. Second, fine roots will penetrate a shallow soil overlying a weathered or well-fractured bedrock or glacial till to anchor the soil-root mass. This directly increases shear strength of the soil mantle on steep slopes. Third, roots around the lateral edges of the root system co-occupy a common soil volume with roots from adjacent root systems. This tends to form a continuous network of roots in the soil within a living stand of trees. This becomes especially important where shallow soils overlie a hard bedrock surface with few fractures or joints. Under these conditions, tree roots increase the stability of slopes mostly by tensile strength of lateral roots.

Researchers have asked whether roots in the zone of soil shear fail in shear or tension. Tree roots will fail in shear if the roots are held rigidly in the soil matrix and the shear zone is very narrow--only a few millimeters wide. Tree roots will fail in tension whenever the shear zone is wide enough to allow roots crossing the shear zone to deflect, elongate, and develop their maximum tensile strength. Live roots 5 to 10 mm in diameter possess enough tensile strength to cause the surrounding soil to yield as these roots deflect across a shear zone, and this encourages the development of maximum root tensile strength.

The authors feel that shear zones are relatively wide in the forest soils studied for this report and that the majority of tree roots fail in tension. There is evidence that the width of these shear zones can range from 7 to 25 cm. Shear zones in this range have been observed on the margins of slope failures that include tree roots and around root masses of windthrown trees on deep soils. Some of these root masses show a rotational mode of failure with broken tree roots extending from the shear surfaces of the soil-root mass. Studies of slope failures in soils over glacial till in Alaska (Wu 1976) indicate that the expected width of soil shear zones will range from 7.5 to 30 cm and that the expected mode of root failure is in tension.

Root decay begins as soon as a tree is felled and affects the smallest roots immediately because of their thinner bark, less resinous wood, and large surface area relative to wood volume. This causes a rapid decline in numbers of fine roots throughout the rooting zone of an individual tree, together with a sharp decrease in the tensile strength of the remaining roots.

Several effects on the stability of steep slopes may be expected as a result of tree felling. The total tensile strength per unit area of fine roots, which help anchor shallow soils to fractured or weathered bedrock or glacial till, will decrease rapidly within 2 or 3 years after felling. This causes a plane of weakness to develop at the soil-bedrock or soil-till interface where slope stability becomes increasingly dependent upon the shear strength of the soil itself.

Tree felling also causes a zone of weakness to develop around the lateral edges of the soil-root mass of each tree, and this zone steadily widens with time. When viewed from above, the root systems of a living stand of Douglas-fir would be analogous to a patchwork quilt of individual root systems joined at their edges by large numbers of fine roots that co-occupy the soil. After felling, these root systems begin to resemble islands as the fine roots in the soil around the lateral edges of the root systems dwindle in numbers and strength. The margins of the root systems continue to retreat leaving only the larger roots in the soil.

Although these larger roots may retain considerable tensile strength with time after felling, the fine roots disappear within a few years. On windthrown trees, the larger roots around the lateral edges of the root mass are composed of long, ropy laterals, 1 to 2 cm in diameter and larger. The ends of the laterals divide into smaller branches, each with fans of fine roots firmly connected to the soil. Other short, fine roots branch directly from the laterals at intervals along their length. The fine roots decay rapidly after felling and leave the laterals with only a minimal connection to the soil.

The concept of zones of weakness in the soil co-occupied by fine roots from adjacent stumps is illustrated by figures 14 and 15. The road shown in figure 14 was photographed in 1974. Right-of-way timber had been felled during the winter of 1971-72; the slope above the road failed sometime later. The stumps at the upper end of the slope failure are shown close-up in figure 15. The man is standing at the edge of a fissure that has opened in the zone of weakness halfway between the two stumps (arrows). The slope failure has undercut the lower stump and, in this extreme instance,

Figure 14.--Slope failure above a logging road.

Figure 15.--Separation of two stumps at upper end of slope failure.

the soil-root mass with the stump at its center has pulled away from the upper slope. The authors believe that many slope failures in timber harvest areas on steep slopes with shallow soils are initiated by the creation of zones of weakness under and around individual tree stumps, as illustrated in these figures.

The authors conclude that the finer roots (1 cm and smaller) have the greatest effect upon slope stability. It is this size class that is the greatest component of all roots around the periphery of individual tree root systems, and it is this size class that shows the greatest change in numbers and strength with time after felling. Measurements by Bishop and Stevens (1964) in Alaska of the increased frequency of landslides within a few years after timber harvest support this hypothesis.

Other evidence of the connection between the frequency of mass failures and tree felling is shown in an inventory of landslides on a single Ranger District in western Oregon following an intense rainfall period (Gresswell and others 1976). The area included in the inventory contained lands with a high potential for landslides and with Coast Douglas-fir as its principal merchantable timber species. The mass failures were classified as "unit-associated" (clearcut but not related to roads or landings), "road-associated," and "natural" (having no apparent relationship with management activity). The percentages of mass failures associated with each of these three categories were: unit-associated, 77 percent; road-associated, 14 percent; and natural, 9 percent. The 190 mass failures associated with timber harvest areas were subdivided by time after felling as follows: 0 to 3 years after felling--120 failures (65 percent); 4 to 10 years after felling--54 failures (29 percent); and 11 years or more after felling--12 failures (6 percent). The results of this inventory emphasize that the removal of timber from an area with a high potential for slope failure can drastically affect slope stability. Also, the number of mass failures per year in timber harvest areas is greatest within the first 3 years after felling. This corresponds to the period of most rapid decline in both numbers and tensile strength of Coast Douglas-fir roots in the 0 to 1 cm size class as shown in this study.

The values of total root tensile strength per unit area of soil, as shown in figures 12 and 13, represent the maximum root tensile strength and serve as an index of the tensile strength actually available for slope stability. Only a portion of this total root strength will be effective in an actual situation because not all

roots develop their ultimate strength at the same time. When a soil-root mass is at the point of incipient failure, some of the roots have already failed, while others may be at the point of failure, and still others have not yet reached their peak strength.

The authors are developing equations that apply tensile strength per unit area of soil (fig. 12 and 13) to the analysis of slope stability. The equations will be used to estimate the effective tree root strength that acts as an apparent cohesive force and that increases total shear strength of the soil. Following field testing of the equations, results of the work will be reported.

CONCLUSIONS

The results of this study show that the tensile strength of individual fresh roots is distinctive for Coast and Rocky Mountain Douglas-fir. The tensile strength of fresh Coast Douglas-fir roots from Oregon appears to be identical to the strength of fresh Coast Douglas-fir roots from British Columbia. Although stronger than roots of the Rocky Mountain variety when fresh, roots of Coast Douglas-fir lose their strength more rapidly. For example, a fresh Rocky Mountain Douglas-fir root is only 35 percent as strong as a fresh root of the same diameter from a Coast Douglas-fir, but 120 months after felling, a Rocky Mountain Douglas-fir root is 2.2 times as strong as a root from Coast Douglas-fir.

The numbers of roots per unit area of soil also show a sharp decline with time after felling. Rocky Mountain Douglas-fir roots are less numerous than Coast Douglas-fir when live, but are more numerous than Coast Douglas-fir 30 months after felling.

The combination of the numbers of roots per unit area of soil and the tensile strength of individual roots gives the total root tensile strength per unit area of soil. These values decline rapidly with time after felling. Coast Douglas-fir shows a loss of about 82 percent of its strength per unit area of soil within 30 months after felling for roots 1 cm and smaller. By comparison, Rocky Mountain Douglas-fir loses only 64 percent of its total strength in that period of time. By 144 months after felling, Rocky Mountain Douglas-fir has about 3.6 times as much total root strength per unit area of soil as Coast Douglas-fir.

The values of root tensile strength per unit area of soil represent the maximum strength that would be developed if each root arrived at its peak strength at the same time. Tensile strength per unit area, as shown in this paper, may be used as an index of the value of Douglas-fir root strength in slope stability. Equations for calculating slope stability that incorporate the cohesive force of roots, and the field testing of the equations, will be covered in future reports.

The authors conclude that Douglas-fir roots 0 to 1 cm in diameter are the most effective in increasing the stability of timbered slopes. This is based upon the rapid decrease in numbers and tensile strength of roots in this size class with time after felling. These changes match the high frequency of landslides the first few years following timber harvest on slopes with a high potential for failure in western Oregon and central Idaho.

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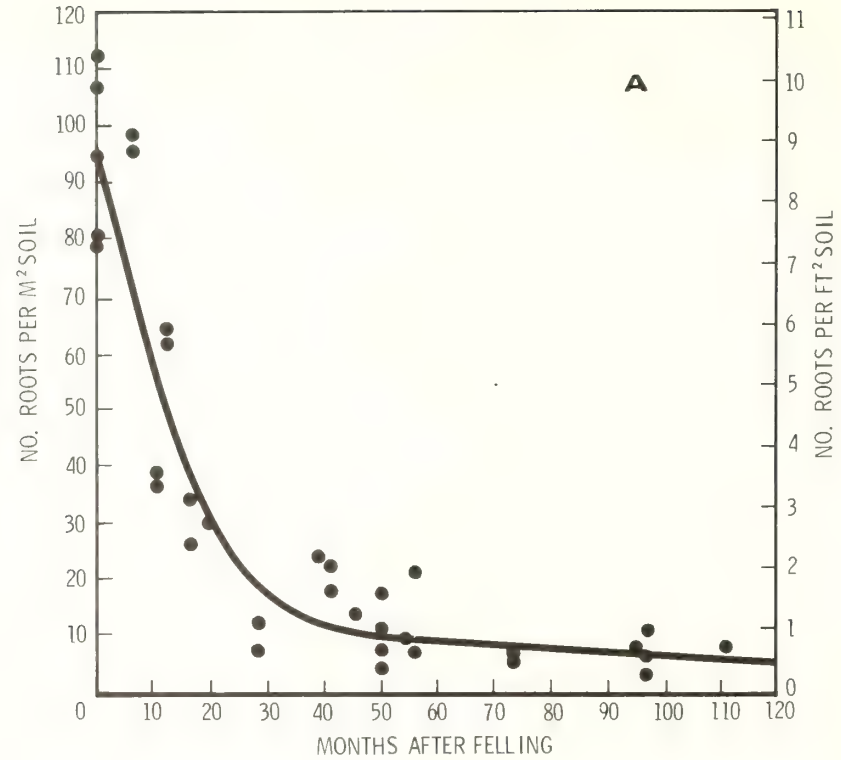
APPENDIX

Raw Data Plots for Various Size Classes



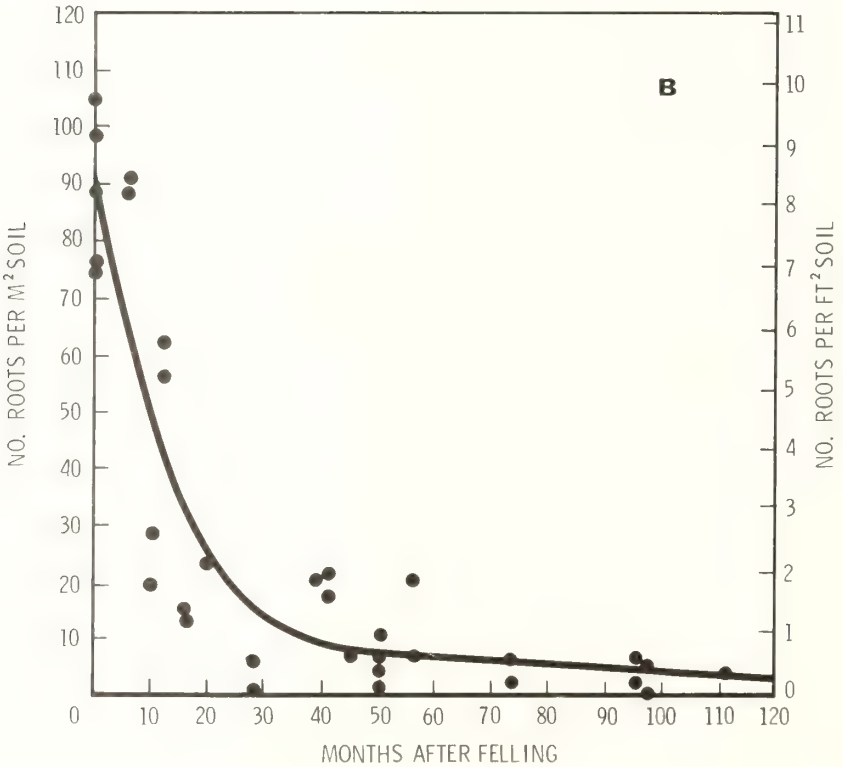
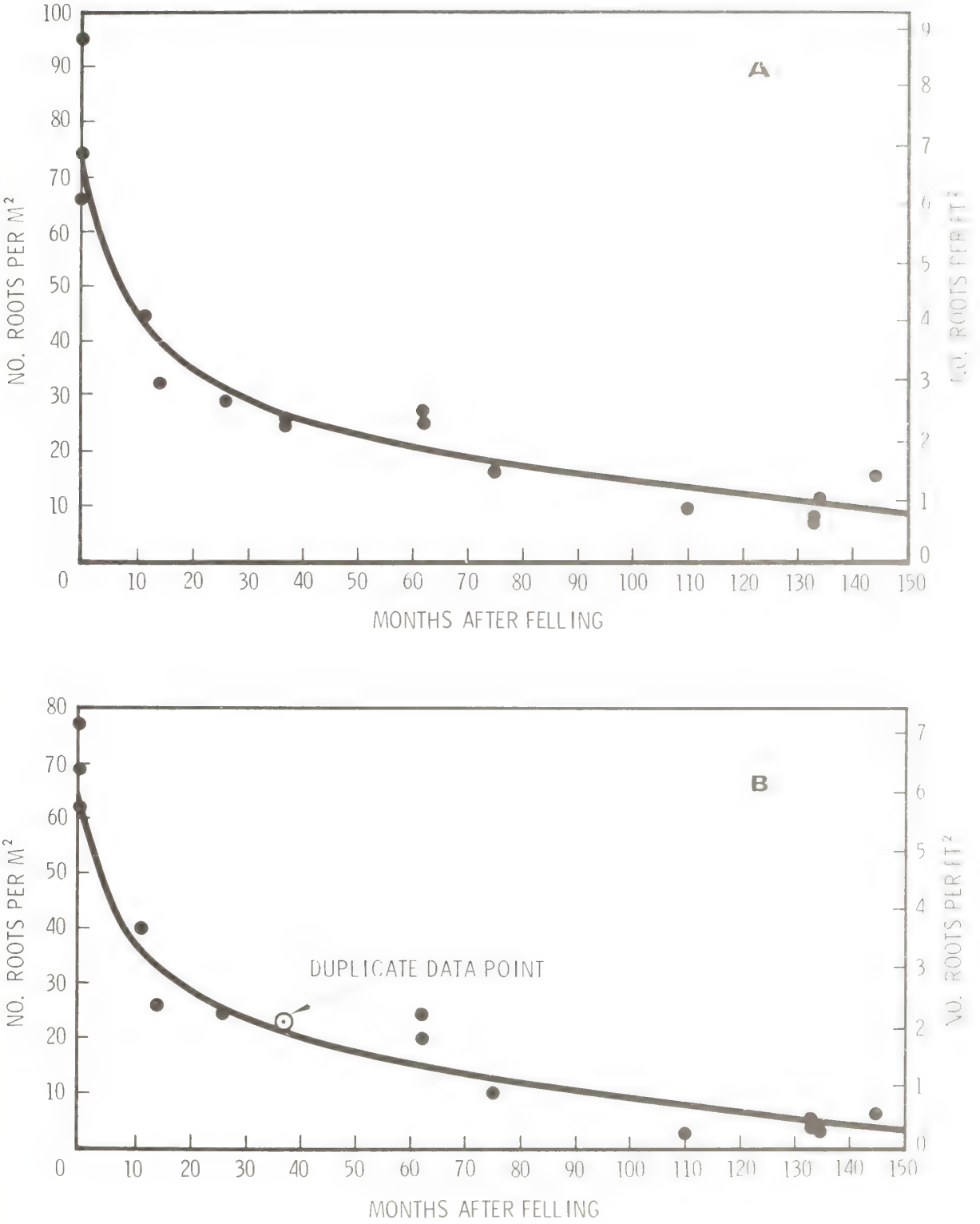


Figure 16.--Decline in numbers of Coast Douglas-fir roots per unit area of soil: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class.* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*



raw data for the 0 to 4 mm (0 to 0.16 in) size class.

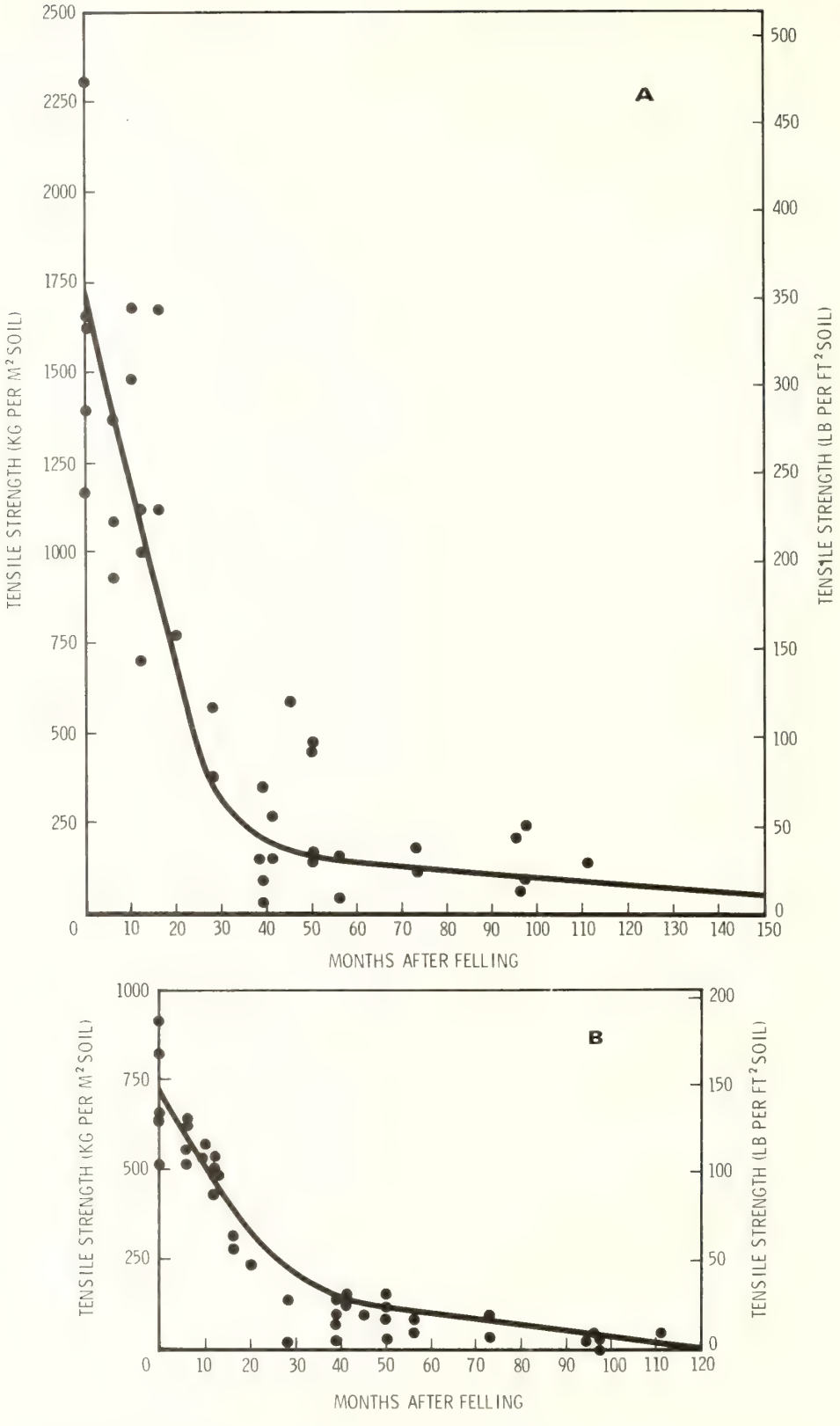

A
TENSILE STRENGTH (KG PER M² SOIL)
TENSILE STRENGTH (LB PER FT² SOIL)
MONTHS AFTER FELLING
B
TENSILE STRENGTH (KG PER M² SOIL)
TENSILE STRENGTH (LB PER FT² SOIL)
MONTHS AFTER FELLING

Figure 18.--Decline in tensile strength per unit area of soil for Coast Douglas-fir: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class;* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*

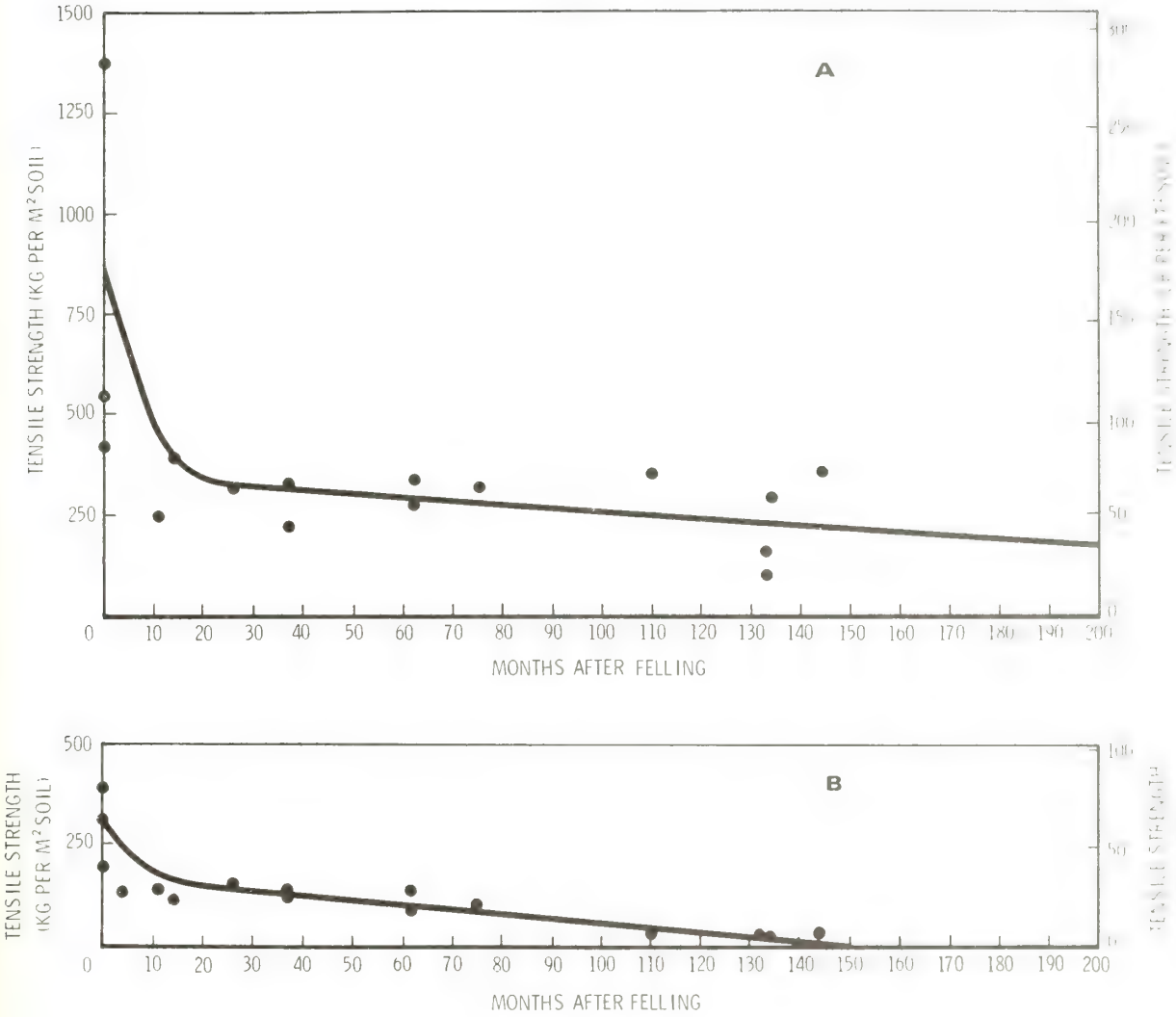


Figure 19.--Decline in tensile strength per unit area of soil for Rocky Mountain Douglas-fir: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class;* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*

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Numbers of roots per unit area of soil and tensile strength of

Rocky Mountain varieties of Douglas-fir. Reduction in number of roots and root tensile strength were combined to estimate total tensile strength per unit area of soil. Within 30 months after felling, Coast Douglas-fir lost 86 percent of its total root tensile

as Rocky Mountain fir roots when live, but decay at a faster rate

KEYWORDS: tree
Mountain Douglas-fir, slope stability

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POTENTIAL WATER YIELD RESPONSE FOLLOWING CLEARCUT HARVESTING ON NORTH AND SOUTH SLOPES IN NORTHERN IDAHO

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RESEARCH SUMMARY

The hydrologic response of small clearcuts on north and south slopes in northern Idaho was investigated. On the north slope, substantial gains (27 to 35 cm) in potential water yield per year resulted from (a) removal of transpiring surfaces associated with plant cover, (b) elimination of snow interception by a closed-canopied forest, and (c) gradual reoccupation of the soil mantle by invading herbaceous species. On the south slope, small to moderate gains (4 to 11 cm) in yield resulted from clearcutting, at least in 1973, the year studied. In earlier years, the gains probably would have been negligible. Site factors that compensated for clearcutting kept gains in yield small to moderate on the south slope. Initial forest losses from interception were light because of the open-canopied structure of the timber and windiness at treetop level. In the clearcut, water gains from reduced transpiration were more than used up within 4 years by invading shrub species. The south slope clearcut was subjected to other sources of water loss also.

INTRODUCTION

In the heavily timbered, snow dominated landscape of northern Idaho, the problems of watershed management differ from those of less heavily timbered and water-short regions. "The question is not so much how to increase water yields from the snowpack, but rather, how to safely dispose of the increased water yields that accompany timber harvesting...." (Satterlund and Haupt 1972). The Forest Service in cooperation with the University of Idaho and Washington State University has a comprehensive program underway in snow hydrology and snow management at Moscow, Idaho. The research program consists of three parts: (1) studying the physical-biological processes, (2) evaluating manipulative treatments on individual plot areas, and (3) testing the most promising findings on monitored watersheds.

This paper describes one segment of the research program--a plot study to determine the effect of timber harvesting and early site recovery on potential water yield under divergent conditions existing on north and south slopes in a prime timber-producing zone. Results from this hydrologic investigation should add to the knowledge base needed to better estimate how much, where, and when to expect water yield increase from clearcutting practices.

BACKGROUND INFORMATION

Previous research on the integrated effects of timber harvest, snow hydrology, and soil water has been limited. Packer's (1962) analyses of snow data collected on the Priest River Experimental Forest in northern Idaho showed that a change in canopy density from a completely closed to a completely open condition increased the average water equivalent (WE) uniformly 10.7 cm. This average relation, according to Packer, occurred regardless of differences in year, elevation, or aspect. He inferred that increase in WE at the time of maximum snowpack was due primarily to loss by interception, and subsequent evaposublimation within tree canopies.

Anderson (1956) reported much larger gains in the central Sierra Nevada of California; on the average, the April 1 snowpack contained 28 cm more water in large open areas than in dense forest. He explained that the difference may represent the net effect of three factors: loss by interception, difference in winter melt, and blowing of snow by wind.

Recent findings in the West have challenged the importance of loss by interception, particularly in the high-elevation forests of the central Rocky Mountains (Hoover and Leaf 1967; Dietrich and Meiman 1974; Gary 1974) and of the central Sierra Nevada (Smith 1974). However, in the midelevation forest of Priest River Experimental Forest recent lysimetric data indicate that for some forest-terrain situations winter loss by interception remains important (Haupt 1972b). This latter evidence substantiates what Packer inferred in 1962 from snow course data.

The studies reported by Packer and Haupt dealt only with the snowpack and snowmelt and not with changes in soil water storage. Elsewhere in the West the literature contains little data on soil water storage at different slope exposures in the timbered snow zone. Bethlahmy (1973) concluded by examining flow patterns of 14 mountain streams that north slopes, with their denser vegetative cover and deeper soils, generally will lose more water through transpiration and retain more water against the pull of gravity than south slopes. South slopes will lose less water through transpiration and will yield more water to deep seepage. On the other hand, Tew (1967) studied the effect of slope exposure on water use by aspen in central Utah and found that the largest amount of water was removed by vegetation on a western exposure. He also reported that amounts of water removed from north and south aspects were similar.

Cutting effect, or site recovery, in the snow zone may involve considerable time. Snowpack increases persist for long periods after forests are cut (Hoover 1969). In contrast to the slowly diminishing snowpack after timber removal, soil water gains tend to decrease quite rapidly. In a Central Sierra study, savings dropped by one-half in 4 years after a selection-type cutting (Anderson 1963). After clearcutting, Zeimer (1964) found that resultant increases in water stored in the soil would fall to zero by the 16th year. Neither study documented the effect that slope exposure or plant habitat type might have on the rate of site recovery.

DESCRIPTION OF STUDY AREA

The study was conducted in the midelevation zone of Priest River Experimental Forest. The specific study area overlapped onto both slopes of an east-west oriented ridge between an elevation of 1,300 and 1,400 m. The south (180°) slope includes the *Pseudotsuga menziesii/Physocarpus malvaceus* habitat type on 44 to 52 percent slope gradients. Stand heights range from 27 to 39 m with crown closure of 20 to 30 percent. The open overstory consists of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco), western white pine (*Pinus monticola* Dougl.), western larch (*Larix occidentalis* Nutt.), and grand fir (*Abies grandis* [Dougl.] Forbes) and the understory contains a rich mixture of shrubs dominated by ninebark (*Physocarpus malvaceus* [Greene] Kuntze).

The north (335°) slope is classified as *Tsuga heterophylla/Pachistima myrsinites* habitat type (Daubenmire and Daubenmire 1968) on 38 to 48 percent slope gradients. Stand heights vary 37 to 49 m with crown closure of 90 to 100 percent. The dense overstory consists of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), western redcedar (*Thuja plicata* Donn), and western white pine, and the understory contains a trace of low, herbaceous plants.

Soil profiles on both slopes are similar except [illegible] the lower horizon. The upper mineral horizon [illegible] volcanic ash; the next horizon, about 10 cm thick, [illegible] Mazama eruption. Both are silt loam in texture [illegible] fragments of granite and schist, lies below the ash [illegible] depth of more than 100 cm on the north slope, but [illegible] south slope, this horizon contains more rock fragments [illegible] north slope is composed of granite and schist [illegible] those in the glacial till immediately above. [illegible] since the bedrock is believed to be quartzite [illegible] slope. Average depth to bedrock is greater on the north slope [illegible] on the south slope (137 cm).

The climate is influenced by the Pacific Ocean [illegible] are cool and wet. Storms and accompanying winds generally [illegible] southwest, and west. Summers are dry and most of the annual precipitation [illegible] falls during winter in the form of snow and rain. Precipitation [illegible] 1973, was 72 cm, the lowest total recorded since 1930. The months [illegible] and August, were extremely dry.

TREATMENT AND CONTROL PLOTS

The treatment plots were located in north-facing and south-facing clearcuts, both having been logged earlier in 1968 and 1969, respectively. Plots were located during autumn 1972 and, therefore, the information reported in this paper deals primarily with the postperiod, November 1, 1972, through November 19, 1973.

Each clearcut was small, 61 by 198 m, with its long axis oriented north-south. The north slope clearcut (station 44) opened onto the lower side of a much larger unit; the replication on the opposite slope (station 50) opened onto the larger unit at the crest of the main ridge (fig. 1).

Slash on the south clearcut was removed by skidding during autumn 1969; consequently, much of the deciduous woody shrub understory was severely broken, crushed, or grubbed out, but not burned. Understory vegetation was almost absent on the north slope; slash there was piled by tractor into a windrow during autumn 1968 and burned.

The treatments consisted of a "revegetated" plot where the vegetative cover was in the process of recovering, since slash disposal, and a "bare" plot on which the vegetative cover was physically removed in 1972 (but not burned) for the second time. The bare plot was assumed to approximate the ground surface condition the first year following disposal of slash when ground cover was at a minimum. Each treatment plot, about 25 m square, was positioned near the center of the clearing.

The forested or "control" plots represented by stations 47 and 42 were deep in the uncut forests west of the treatment plots (fig. 1).

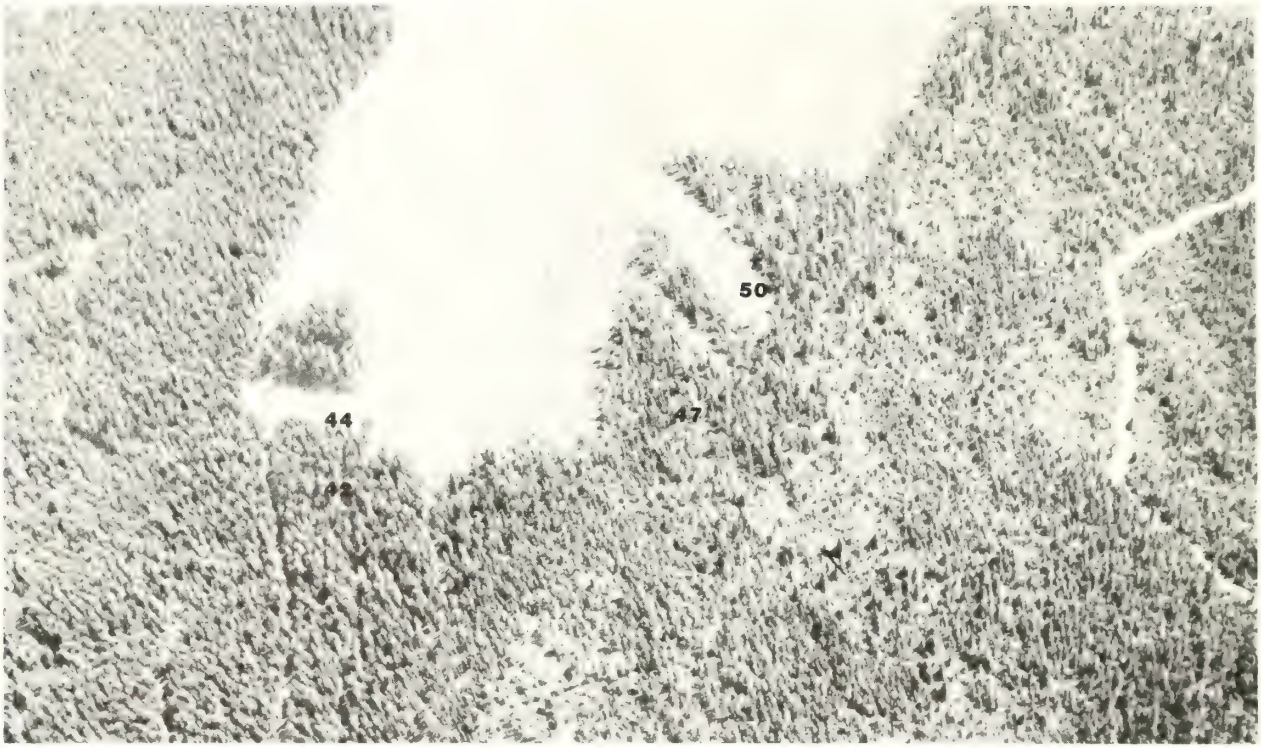

Figure 1.--Stations 42 and 44 (north slope) and stations 47 and 50 (south slope), Priest River Experimental Forest. Arrow denotes general wind direction south to west.

INSTRUMENTATION AND MEASUREMENTS

Rainfall and snowfall were indexed near each plot location from November 1, 1969, through October 31, 1973, by means of snow courses, recording rain gages, and snow lysimeters. Two parallel snow courses, located on the contour of each slope, traversed the clearcut and adjacent forest. Each course included 16 nonrandom snow sampling areas (10 in the clearcut and 6 in the forest). Water equivalent was measured periodically with a federal-type sampler during the accumulation-melt period, but only those readings taken at peak snowpack are discussed.

Precipitation in the clearcut opening and through-fall in the forest were recorded by a Belfort rain gage equipped with stereo orifice and modified windshield (Haupt 1972a). A single gage was positioned midway across the clearcut and another under the tree canopy on each forested plot.

Percolate was collected from snow lysimeters (Haupt 1969), which were operated from November 1 through May 31. Lysimeters provided point measurements of net precipitation--precipitation that percolated through the snowpack during rainy periods or ultimately entered the soil mantle as the snowpack melted. They were positioned near the rain gages. In the forest, they were located beneath a canopy configuration similar to that above each rain gage.

The climatic record also included temperature, wind travel, incoming solar radiation, and atmospheric relative humidity at each station. The relative humidity and temperature were obtained with a hair and bimetallic hygrothermograph, radiation with a mechanical pyranograph, and wind travel with a three-cup totalizer. These data were used to calculate potential evapotranspiration (PET) using the Penman equation with the wind function of Wright and Jensen (1972).

During autumn 1972, neutron probe access tubes were installed by means of a method described by Cline and Jeffers (1975). These tubes were laid out in a random pattern about 10 m apart with three tubes in each forested plot, revegetated plot, and bare plot. A few tubes were placed to a depth of 183 cm, but bedrock forced termination of most tubes at a shallower depth. Despite these limitations, probe readings were taken in each tube to a depth of at least 137 cm.

To measure soil water, a neutron probe manufactured by Troxler Electronic Laboratories, Inc., was used. Calibration was performed with volumetric samples from special calibration plots. Because of good consistency between volumetric samples and readings from the manufacturer's rating curve, no correction was needed. Soil water data were collected at 15-cm depth increments in autumn 1972 and spring, summer, and autumn 1973.

The study design did not include the statistical sensitivity of taking pretreatment measurements to determine if inherent site differences existed. The drastic treatments used were assumed to overcome these. This proved to be the case in a Colorado study by Dietrich and Meiman (1974).

RESULTS

Soil water.--A graphic presentation of soil water content from April 4 to November 19, 1973, is shown in figure 2. The three plot conditions are presented in each part (A and B) of the figure and represent the average of three tubes in each plot. Examination with reference to the bare plots suggests that water contents in the profile had begun to stabilize by the first part of June after fluctuating in early spring. Drainage from these soils was assumed to be substantially reduced and field capacity approached due to decreasing hydraulic conductivity (Baver and others 1972, p. 381-384). June 4 was chosen as the beginning of the drawdown season for both slopes and estimated evapotranspiration (ET) water losses were determined for the six profiles from this date to August 27 when they contained the least water.

A Duncan's Multiple Range Test at the 5 percent level of significance was applied to the means (water loss), and results are given in table 1. These mean losses do not include 2.5 cm of rain received during the first 3 weeks of June. The June storms provided the last important period of rain until August 30 when 1.8 cm of rain fell. Table 1 shows that, of the revegetated-forested plots, the north slope revegetated plot lost the least water to ET during this period.

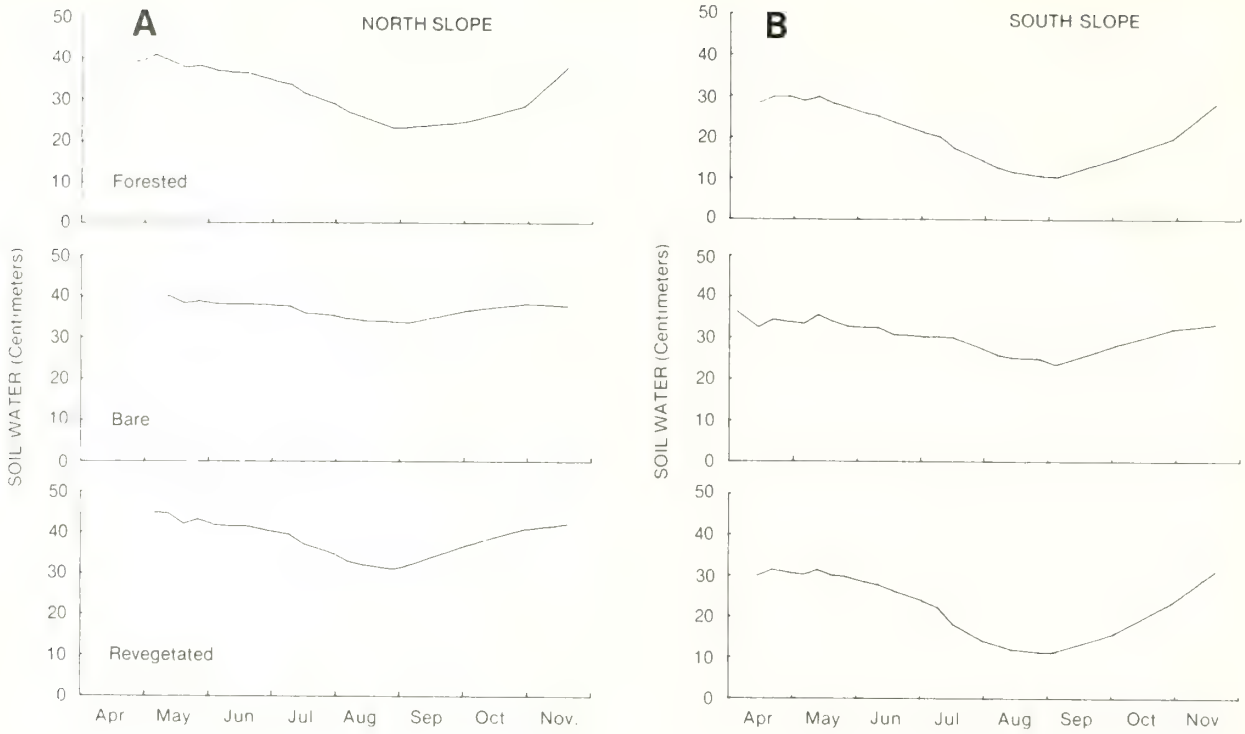

Figure 2.--Seasonal water content in 137-cm profile for (A) north slope plots and (B) south slope plots.

Table 1.--*Duncan's multiple range test of six water loss means at the 5 percent level of significance*

Treatment	Mean (cm of water)[1]	
North slope, bare soil	4.2	A
South slope, bare soil	7.7	B
North slope, revegetated (5 years since logging)	10.4	C
North slope, forested	13.5	D
South slope, forested	15.4	
South slope, revegetated (4 years since logging)	18.4	

[1]Means followed by any letter are significantly different from those means not having that letter.

terrestrial solar
north slope plots.

Although not significant at the 5 percent level, the order of the last three means in table 1 is reasonable in light of conditions existing on these plots. The greater rate of soil loss from the revegetated and forested plots on the south slope is understandable due to greater solar radiation (fig. 5) and therefore greater potential [illegible] of loss from evapotranspiration may also be due to vegetative [illegible] north slope plot contained primarily [illegible] (fig. 4), whereas the forested south slope plot [illegible] nous woody shrubs in addition to trees. [illegible] (1968) suggest greater leaf area [illegible] ous trees. This could contribute to the greater [illegible] with significant amounts of deciduous brush.

In spite of variations in spring maximum water content of [illegible] several similar soil profiles on north and south exposures in the Priest River Experimental Forest contained about 10 cm of water at their driest [illegible]. From this and from results in table 2, we concluded that both forested and revegetated plots on the south slope had depleted soil water reserves to this minimum by August 27. This conclusion is also supported by the water content curves (fig. 2B) that inflect toward the horizontal starting in late July.

However, north slope plots did not lose water to a minimum of 10 cm nor did the loss rate of the forested plot appear to decrease as did those on the south slope during August. The curve for the north slope revegetated plot did inflect in August (fig. 2A), but the minimum water content of the profile was considerably higher than that of the forested plot. This suggests that, unlike the south slope which appeared to be completely reoccupied within 4 years, a 5-year period was not sufficient time for vegetation to completely reoccupy the soil volume after clearcutting.

The bare plots in figure 2 lost more water at the beginning of the growing season season than they did as the soil surface dried. Starting in mid-July, the south bare plot shows an increased rate of water loss not shown by its north slope counterpart. The shrubs on the south aspect were characterized by extensive fibrous, horizontal root systems. The tendency of shrubs adjacent to the bare plot to branch their roots may account for the accelerated water losses in July and August, particularly in the

Figure 4.--(A) Undisturbed forested plot on north slope. (B) Revegetated plot on north slope clearcut. Note dominance of herbaceous species, fireweed (Epilobium angustifolium L.).

Table 2.--*Water content in 137-cm profile at spring field capacity and summer minimum*

Treatment	North slope				South slope			
	Spring field capacity		Summer minimum		Spring field capacity		Summer minimum	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
	Cm		*Cm*		*Cm*		*Cm*	
Forested	36.7	3.5	23.2	1.1	25.4	3.8	10.0	3.2
Bare	38.2	3.3	34.0	4.0	33.4	2.2	25.7	3.0
Revegetated	41.5	4.0	31.1	4.5	29.4	4.5	11.0	2.8

30- to 60-cm depth zone. (The borders of the bare plot were not trenched to sever roots.) Shrubs on sites like this may recover the total volume of soil water in less than 4 years largely because of their ability to grow back rapidly from root stocks. These shrubs will recover quickly even where aboveground foliage is completely destroyed by broadcast burning after logging (fig. 5).

Figure 5.--(A) Undisturbed forested plot on south slope. (B) Revegetated plot on south slope clearcut. Note dominance of deciduous woody brush, ninebark. (C) Adjacent large clearcut where understory brush and logging slash were broadcast burned the fall of 1968.

Frequent rains between August 30 and November 19 succeeded in recharging the soils to water levels observed the previous spring. The profiles with greatest water contents at the end of August tended to recharge more quickly (fig. 2, bare plots and north revegetated plot) than those that had been depleted of water by trees and dense brush. In the fall, the tree-covered and dense-brush plots recharged slowly at first, then more rapidly, suggesting that higher order vegetation was still removing water from these profiles. By the time the first snows covered the ground in mid-November, the soils were almost fully charged and in condition to add ground water reserves.

Winter precipitation.--Soil water storage is but one component to consider in determining the potential water yield budget. At Priest River, where a major portion of the precipitation falls during the dormant season, snow storage, winter release (rain percolate and melt from winter snowpack), and spring melt are important considerations. For the period November 1, 1972, through May 31, 1973, the mean peak snowpack (WE) and seasonal totals of precipitation and lysimeter percolate are presented in table 3. To illustrate the effectiveness of timber harvest, a comparison of gains in the clearcut is shown in table 4.

From November 1 to May 31, the lysimeter in the north forest registered the least amount of total percolate, but the north clearcut measured the most. The south forest and south clearcut ranked between the two extremes. The north clearcut showed the greatest gain (19.6 cm) after timber removal; in contrast, the south clearcut showed but a slight increase (2.9 cm).

Table 3.--*Mean peak snowpack (WE)*[1] *and seasonal*[2] *totals of precipitation and lysimeter percolate for study plots, water year 1973*

WE		Modified Belfort rain gage		Lysimeter percolate	
		Centimeters			
North forest	14.0	South forest	42.9	North forest	38.9
South forest	18.3	South clearcut	49.4	South forest	51.2
South clearcut	25.9	North forest	49.5	South clearcut	54.1
North clearcut	32.3	North clearcut	60.9	North clearcut	58.5

[1]Clearcut means based on 20 samples, forest means based on 12 samples.
[2]November 1, 1972, through May 31, 1973.

Table 4.--*Comparison of gains in clearcut based on three indexing techniques for the period November 1, 1972, through May 31, 1973*

Slope exposure	Mean peak snowpack	Modified Belfort rain gage	Lysimeter percolate
	Centimeters		
North	+18.3	+11.4	+19.6
South	+ 7.6	+ 6.5	+ 2.9

The snow courses, which provided broad spatial sampling of the plots, showed an identical order of ranking in terms of WE. Again, the north forest proved the least effective in storing snow at any time during winter. With timber removal, the WE increased by 18.3 cm on the north clearcut. The difference between south forest and south clearcut was much less, 7.6 cm, but exceeded the same comparative difference between lysimeters.

Precipitation totals collected in rain gages deviated from the above pattern; both south slope gages caught less precipitation than gages on either the north forest or north clearcut (table 3). The south slope catch became suspect early. In a previous report, Haupt (1972a) ascribed the lower catch to aerodynamic (shear) stresses associated with rain gages on windswept, exposed (south) slopes. A more subdued effect of wind on gage catch was noted on sheltered (north) slopes.

The relatively large difference (10.4 cm) between the north forest rain gage and north forest lysimeter was not expected, however, because both instruments had been placed under very similar tree canopies. This relationship held for previous years of record (1969-72) although the differences were not as great (unpublished data on file, Forestry Sciences Laboratory, Moscow). Perhaps the canopies above the rain gage became more porous during snow loading, allowing greater through-fall, and/or that the surface of the snow column forming in the lysimeter was subjected to some minor wind scouring and evaposublimation, resulting in some loss in total percolate. In view of the lower readings for snow courses in the north forest, the conclusion was that the lysimeter total was probably more representative of conditions under the timber stand than precipitation.

The anomalous reading given by the south forest rain gage notwithstanding, it is significant that less snow storage and lysimeter percolate occurred in the dense north forest than in the less dense south forest. There is no evidence to show that precipitation incident to the south slope was substantially greater than that which fell on the north slope. Rather, the disparity is attributed to greater tree interception in the north forest and to subsequent evaposublimation exchange between the canopies and atmosphere.

The physical processes involved are complex and detailed examination is beyond the scope of this paper. Several conditions probably contributed to greater interception losses in the north forest. First, and perhaps most important, the north forest, which had greater crown closure and thicker canopies, was capable of catching and holding considerably more snow (or rain) during a storm. Second, the north forest was afforded topographic shelter from prevailing winds and, as a consequence, less snow (or rain) was scoured or shaken from the canopies by this force. Third, less solar energy was received after storms in the north forest; so less canopy-held snow was transformed into drip and more remained intact in the canopies (Haupt 1972b). Fourth, the three conditions above provided more surface area and exposure hours for canopy-held snow to be acted upon between storms by evaposublimation processes. Finally, the north slope timber, in particular the south-facing portion of the upper tree crown, received adequate amounts of radiant energy at periods that were optimum for evaposublimation (not measured). During the dry winter-spring of 1973, optimum periods were numerous because of the low storm frequency. Over the 7-month period, total loss back to the atmosphere was estimated to be high.

The lower snow storage efficiency of the south clearcut, compared to that of the north clearcut, appeared to be closely associated with its position near the ridgetop and exposure to wind and energy sources. For instance, mean wind travel (1969-73) at ground level was twice that in the north clearcut (table 5). Prevailing winds scoured snow in the opening, carried some of it over the ridge, and deposited it in a cornice to the lee of the ridgetop. In years prior to 1973, the cornice had accumulated significantly more WE by mid-March than would have occurred if the opening had not

Table 5.--*Four-year mean*[1] *seasonal wind travel at ground level in clearcut and forest, by aspect*

Wind travel	Clearcut	Forest
	Meters minute^{-1}	
North	51	25
South	103	47

[1]November 1 through May 31, water years 1970-73.

existed on the south slope (Haupt 1973). This accumulation implies that some "losses" from the south clearcut may have reappeared as "gains" in the cornice. Because the north clearcut measuring sites were located well downslope and slightly upwind (fig. 1), it is unlikely that any of the eroded snow from the south clearcut was moved beyond the cornice and redeposited there.

The increased wind movement in the south clearcut also suggests the possibility of accelerated evaporation losses from the snowpack. By assuming exposure conditions similar to those reported by West (1959) for windy locations near ridges, the expected evaporation losses (not measured) could have been a few centimeters greater in the south clearcut than in the north clearcut and south forest.

Potential water yield.--Increases in potential water yield could not be estimated without first determining ET loss from the soil profile during the complete growth period, spring through fall. The approach followed was an adaptation of the water-budget technique, in which losses to the atmosphere and to drainage were considered simultaneously. This is at best a tenuous approach associated with assumptions that may not be correct.

The ET withdrawal from April 1 (arbitrarily set as the earliest date for any substantial ET) to June 4 was obtained by comparing actual soil water loss during a week of high evaporative demand in mid-May with potential evapotranspiration (PET) calculated from on-site radiation and other meteorological data. This soil water/PET relationship was then used to estimate ET for the early, snow-free spring period. These values may have overestimated ET loss during the period when deciduous, understory plants were leafing out. The estimated losses appear reasonable, ranging from 3.6 to 6.8 cm (table 6). Greater loss would be expected on south slopes, which receive more solar radiation and wind.

The assumption that drainage from the 137-cm zone was essentially zero by June 4 and that ET became the major component in water loss after this date was applied for the summer period. Little or no rain fell until August 27; so the values in tables 2 and 6 are good estimates of ET for this period.

From August 27 to October 31, precipitation and the rate of recharge became significant parameters in evaluating ET loss. The date that soil water content reached the June 4 value was used as the cutoff point for shifting water loss from ET to potential water yield. An estimate of water loss was then based on rates of water loss shown in figure 2, since these values account for net precipitation. By October 31, any additional water needed to recharge the profile constituted a deficit. By these calculations, the four vegetated plots and the south-slope bare plot had soil water deficits on October 31, whereas the north-slope bare plot produced drainage prior to that date (table 6). Deficits or gains were added algebraically to the seasonal (1972-73) lysimeter outflow in order to close the bookkeeping procedure.

Land type	Lysimeter percolate Nov. 1 - June 1	Estimated transpiration Apr. 1 - June 1	Accumulated [illegible] Nov. 1	[illegible]	Aug. 27 -	(annual)	Potential to
[illegible]	[illegible]	[illegible]	13.5	8.4		25.9	
Bare	[illegible]	[illegible]	[illegible]		6.1		+35.1
[illegible]	58.5	4.7	10.4	.7	.0	58.1	
[illegible]	[illegible]	[illegible]	[illegible]				
Forested	1.2	[illegible]	14.1	[illegible]	.0	38.4	
Bare	54.1	[illegible]	[illegible]		.0	49.7	[illegible]
[illegible]	51.1	[illegible]	18.4	4.8	.0	[illegible]	+4.4

The dense north forest had a potential water yield of 25.9 cm, or 12.5 cm less than the more open south forest (table 6). On the other hand, the last column in table 6 indicates that the greatest gain (35.1 cm) and the most sustained gain (27.2 cm) occurred on the north slope as a result of clearcutting. More modest gains, 11.3 cm and 4.4 cm, respectively, were registered on bare and revegetated plots on the south slope.

Would potential water yields have been comparable in earlier years prior to the soil water study? Evapotranspiration losses vary from year to year, being largely dependent upon energy input in spring and fall and upon rain in summer. The soil profile probably would not hold more than a fixed amount of water. Consequently, the supply available for plant use would be limited until water was added. Since the year (1973) was extremely dry during late June, July, and August and precipitation was above average during September and October, ET estimates are no doubt conservative. In wetter summers, rain input would most likely be lost to the atmosphere; little or no water would be added to deep drainage, thus increasing seasonal ET.

If the above reasoning is accepted, the measurement that best correlates with potential water yield would be lysimeter percolate measured during winter release and spring snowmelt. Differences in lysimeter percolate between forest and clearcut on the north slope were consistently large in previous years of record (1969-72); consequently, gross gains in potential water yield would be expected to be consistently large (unpublished data on file, Forestry Sciences Laboratory, Moscow).

On the south slope, conditions were highly variable. In 2 previous years (1971, 1972) there were no gains in lysimeter outflow in the south clearcut; in fact, compared with the south forest, less outflow was produced. This decline was probably due to greater snow scouring and evaposublimation loss. In 1970, lysimeter outflow in the south clearcut was comparable to the 1973 outflow (unpublished data on file, Forestry Sciences Laboratory, Moscow).

SUMMARY AND CONCLUSIONS

The practice of clearcutting forested lands to improve water yield is widely accepted. The data presented in this study suggest that under certain circumstances potential water yield increase may be high; under other conditions, the increase can range from negligible to moderate. Slope orientation and wind exposure, as well as forest stand density and structure, are important considerations in defining potential water yield increase.

The north slope in this study responded to removal of a mature old stand (western hemlock-western redcedar/pachistima habitat type) by supporting greater depths of snow, higher percolation from the snowpack, and greater amounts of water draining through the soil mantle to ground water reserves. After tractor piling and slash burning, gradual reoccupation of the soil mantle by invading herbaceous species (primarily fireweed) sustained a large part of the soil water gains for at least 5 years.

Greater storage of snow was due primarily to removal of tall, mature, closed-canopied timber that before cutting suspended a large amount of winter snowfall (and rain) in the foliage. This intercepted precipitation, held high overhead, was vulnerable between storms to radiation sources and wind movement at treetop level. It seems reasonable to suggest that the net result was considerable evaposublimation loss back to the atmosphere. The residual snow left in the canopies eventually fell to the forest floor to add to the reduced snowpack.

Removal of the mature old stand (Douglas-fir/ninebark habitat type) on the south slope had a considerably smaller effect on potential water yield. In the first year after clearcutting, the yield increase was only 32 percent of that measured on the north slope. The invading shrub species (primarily ninebark) rapidly reoccupied the soil mantle. After 4 years of recovery, the shrub monoculture extracted probably more water from the soil during the extremely dry summer than did the original tree overstory-shrub understory. Had there not been greater snow storage during the dormant season to compensate for water removal, a small increase in potential water yield would not have resulted.

Clearcutting on the south slope created less favorable conditions for storing additional snow and producing an excess of percolate into the soil mantle. Because of more open spacing of mature trees, snowfall easily penetrated to the ground surface. Furthermore, the prevailing winds and high incident solar radiation caused more of the intercepted snow to either blow off and descend to the forest floor or melt in place and fall as drip. By inference, less evaposublimation occurred and therefore the potential for interception savings to accrue after timber removal was also greatly reduced. In addition, the exposed clearcut received the brunt of the wind and lost snow by scouring and perhaps by accelerated surface evaposublimation. At the end of melt season, the net effect was a slight excess of percolate over that which occurred in the south slope forest. In earlier years, under different weather patterns, an excess of percolate might have been nonexistent.

These results apply only to one unreplicated set of [illegible] two climax habitat types and under the sequence of climatic events recorded. If the specific data on potential water yield increase are extrapolated to other old-growth timber sites with similar terrain and habitat type, it should be done with the above limitations in mind. However, the principles underlying the occurrence of these data can be readily applied elsewhere.

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1977. Potential water yield response following clearcut harvesting on north and south slopes in northern Idaho. USDA For. Serv.

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KEYWORDS: soil moisture content; clearcutting; snowmelt infiltration; canopy interception; logging hydrology

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RATIONING WILDERNESS USE: METHODS, PROBLEMS, AND GUIDELINES

George H. Stankey and John Baden

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RESEARCH SUMMARY

Wilderness managers can regulate ecological and social impacts by implementing one or more of five basic rationing systems: reservations, fees, queuing, lottery, or merit. Each system has advantages and disadvantages for both administrators and users. Managers must consider the effect on user groups, administrative experience with the rationing system, acceptability to users, difficulty of administration, efficiency, principal way impacts are controlled, and effect on user behavior.

Managers should strive to control environmental and social impacts, not merely visitor numbers, with a minimum of regimentation. The following guidelines will help managers implement effective rationing: (1) Know both the wilderness and its users, (2) Ration only when less restrictive measures fail, (3) Combine rationing systems to help minimize costs to users and administrators, (4) Adopt rationing systems that require users to judge the relative value of the opportunity, (5) Monitor and evaluate rationing programs.

INTRODUCTION

One major fact confronting our society today is that the stocks of natural resources from which we derive our material and social wellbeing are not infinite. Although it is true that economic and technological advances continually redefine the nature and extent of the natural resource base, it is also true that the days of relatively free and unlimited access to these resources are past. Daily, we are confronted with headlines that warn of impending shortages and the need to ration our consumption of such things as gasoline, fuel oil, and natural gas.

The need to control consumption has spread beyond traditional products such as food and fuels. In 1972, Rogers C. B. Morton, then Secretary of the Interior, announced the National Park Service would take actions to limit the number of visitors to backcountry areas in the parks because "our parks are threatened now as never before...we must set new standards of usage." Recently, the Forest Service began limiting the number of visitors in several wildernesses, including the Boundary Waters Canoe Area in Minnesota, the San Jacinto and San Gorgonio in California, and on the Mt. Whitney Trail in the John Muir Wilderness, actions taken in response to rapidly increasing use, and the resulting crowding and resource damage.

The rationing of wilderness use has been a controversial issue (Behan 1974; Hendee and Lucas 1974). One of the important traditional values recognized in the preservation of National Parks and wilderness has been the opportunity for respite from the cares and worries of the everyday world. Numerous studies of wilderness users indicate that one of the principal values derived from wilderness is escape--an opportunity for temporary release from the rules and pressures of everyday life (ORRRC 1962; Hendee and others 1968; Stankey 1973). Freedom of choice and spontaneity of action appear to be key characteristics of what is commonly called "the wilderness experience."

Rationing the use of areas producing such values might seem akin to charging people to go to church. Or, it might simply appear to be an unwarranted bureaucratic intrusion into yet another area of our lives. What justification is there, after all, for restricting access to areas that many people visit to escape the controls and stresses that increasingly characterize modern life?

There is also great concern that rationing decisions avoid or minimize discriminatory or unequitable consequences. The National Park Service, for example, in restricting use on the Colorado River of Grand Canyon National Park, allocated the available openings between commercial concessionaires and noncommercial users. Most of the openings were alloted to the commercial operators. As a result, many private, noncommercial parties have been denied access to the river. In the belief that the commercial-noncommercial allocation was discriminatory, Senator Gary Hart (D-Colo.) submitted a concurrent resolution to the Senate in July 1975 "calling for a fair and equitable allocation of restricted-use outdoor-recreational resources" and requested that the Secretary of the Interior review regulations governing the allocation of use to insure fair and equitable treatment. (Senate Concurrent Resolution 56, July 25, 1975.)

Concerns about excessive or unequitable regulations are well founded. But three important facts place the issue of rationing squarely before us. First, the supply of land that qualifies as wilderness is finite. Currently, about 14.4 million acres have been formally designated for preservation. Estimates vary as to the potential size of the National Wilderness Preservation system (NWPS), but about 40 to 50 million acres (2 percent of the United States) might eventually be classified as wilderness (McCloskey 1966; Stankey 1971). However, although future additions to the NWPS might expand its current size by a factor of three or four, these additions will not increase net capacity. Areas currently unclassified, but possessing wilderness qualities, frequently have substantial use.

Second, wilderness use is steadily growing. Nationally, Forest Service statistics indicate about an 8 percent annual growth rate in wilderness since 1969. Moreover, wilderness use is growing at a faster rate than other forest-based recreation demands such as campground use. Although the current economic situation casts uncertainty on future trends, it seems reasonable to expect further growth, and as a consequence, more problems.

Third, the goals that society has established for the NWPS emphasize that wilderness shall be, first, an area where ecological processes operate as unmodified as possible (fig. 1) and second, an area providing solitude and challenging, primitive recreation (fig. 2) (Hendee and Stankey 1973). While use is to be permitted, it must be consistent with the preservation of the area *as wilderness*. Moreover, management guidelines in the Wilderness Act seem to disallow an "engineering" response to overuse problems; namely, extensive "hardening" of sites, developing facilities, and so forth. Although this approach has been proposed (Zivnuska 1973; Behan 1974), we believe it is both illegal and inappropriate in areas managed for the preservation of natural ecological processes.

Figure 1--A major objective of the Wilderness Act is to preserve natural processes that shaped the land and its community of life--conditions that prevail at this unnamed lake in the Anaconda-Pintlar Wilderness.

should provide the visitor with solitude, or primitive and unconfined recreation, conditions enjoyed by this fisherman in the Pecos ... Mexico.

The extent of overuse varies within and between individual wildernesses (fig. 3). While severe problems exist in some locations, others retain those pristine qualities that originally led to their designation as wilderness. However, as we look ahead, and as we consider the goals of ecosystem naturalness and the provision of a unique recreational experience in light of the supply and demand factors reviewed earlier, rationing will certainly become an increasingly significant issue. In the face of continued increases in use on a relatively fixed resource base, it is unlikely that goals set forth in the Wilderness Act can be achieved unless some management action is taken. Guidelines for regulating wilderness use consistent with physical, biological, and social standards need to be developed (fig. 4). Unless this occurs, the quality of the wilderness experience will deteriorate and unacceptable levels of resource degradation will occur.

Wilderness managers have a variety of tools for coping with excessive impacts (Lime and Stankey 1971). Improving use distributions, providing information to improve user behavior, and establishing regulations to control especially heavy impact, such as restrictions on stock in high mountain meadows, are examples. Direct control in the numbers of users, or rationing, is yet another technique and, as we noted above, has been already implemented on some areas.

Figure 3.--Failure to manage use has severely damaged natural qualities and processes at many locations such as this campsite in the Selway-Bitterroot Wilderness.

These different management techniques can be arrayed along a continuum ranging from those that are lighthanded and subtle to those that are authoritarian and heavy-handed. Gilbert and others (1972) have described this continuum as ranging from manipulative to direct controls. To the maximum extent possible, we believe managers should attempt to utilize the more subtle, lighthanded systems so as to preserve the independence, spontaneity, and freedom from regimentation that are major parts of the wilderness experience (Lucas 1973). But the time will come, and has already come in some locations, where direct rationing of use will be necessary. Our discussion assumes that the more subtle measures have failed to control use impacts and that more direct forms of use control are needed. And we are not alone. A major recommendation of the President's Advisory Panel on Timber and the Environment (1973, p. 46) noted:

> That some system must be established in all wilderness areas to limit use to the reasonable carrying capacity of the area, having in mind primarily the nature of the wilderness experience. Unless such limitations can be devised and enforced, the Panel sees little national gain from the withdrawal of additional forest land for wilderness use since in a relatively few years, overuse could destroy its wilderness character.

Figure 3.--Heavy use can destroy solitude and opportunities for self-reliance. Ecological and social concerns are important in managing wilderness.

ALTERNATIVE SYSTEMS OF RATIONING

Rationing is a procedure for gaining an opening or "slot" in some system. In wilderness, the number of available openings is determined by the area's carrying capacity, a value based upon the manager's judgment as to what constitutes acceptable levels of change in ecological and social conditions (Frissell and Stankey 1972).

Given a relatively fixed number of openings that can be distributed to users, wilderness managers are thus faced with the task of allocating these openings in as fair, efficient, and nondiscriminatory a manner as possible. In the following discussion, we will consider five basic rationing sytems that managers might use to limit visitor use. These include: (1) rationing by advance reservation; (2) rationing by lottery; (3) rationing by queuing; (4) rationing by price; and (5) rationing by merit. Each system has certain advantages and disadvantages that must be defined before any system or mixture of systems is adopted.

Rationing by Advance Reservation

The capacity of a wilderness could be allocated by requiring potential visitors to request, or reserve, an opening in advance. Such a system would operate fairly simply, at least in theory. For example, a calculated daily capacity (say, 100 people at one time [PAOT]) would be distributed to that number of visitors, probably on a first-come, first-served basis. Once that capacity was filled, further requests would either be placed on a waiting list (another way of rationing, as we shall discuss shortly), offered an alternative time period, or returned to the applicant.

The advance reservation system is an advantage to persons who work and live orderly lives. Requesting a specific time implies an ability to foresee obligations and opportunities. It also calls for a certain psychological disposition towards predictable behavior. Thus, a request system tends to discriminate against those who are unable or unwilling to make long-term commitments--the spur-of-the-moment, impromptu sorts of people.

Our knowledge of wilderness users tells us that this system will create problems. In a recent, yet unpublished study of rationing in the San Gorgonio and San Jacinto Wildernesses in southern California, less than 20 percent of applicants planned trips more than 1 month ahead of time.[1] Spontaneity and relatively short planning horizons seem to characterize many wilderness trips.

Among wilderness users, two major subgroups are those employed in professional-technical occupations and students. In many areas, these two groups often comprise over one-half the users. Unforeseen demands on persons in professional occupations often keep them from obligating future time. Students, although they have relatively abundant leisure time, often operate in a fairly unstructured style. Moreover, the degree of certainty about future events for both these groups is probably low. As a result, the request system could discriminate fairly heavily against these two major users of wilderness.

Where free of charge, people make reservations even if there is a low probability that they will ever, in fact, use their privilege. In effect, the reservation is free insurance of the opportunity to go. For example, in 1973 the Inyo National Forest, California, rationed use on the Mt. Whitney trail to a maximum of 75 parties per day. Forest officials estimate that approximately one-half of the reservations resulted in "no shows." People also make multiple reservations to maintain the broadest options until a decision has to be made. Unless no-shows can be allocated, the area will often be underutilized even at times when demand for entry is very high.

Rationing by request also does not discriminate among users on the basis of the relative importance of the wilderness experience; a phenomenon called "suboptimization." For example, a wilderness buff who gains great satisfaction from wilderness could be denied entry by a casual, relatively disinterested visitor whose request happened to be postmarked earlier. The enthusiast might have few alternatives, while the other person might have many. The relative worth of the experience would have little bearing on chances for getting a reservation. Obviously, a perfectly functioning system for marketing reservations would substantially reduce this source of inefficiency.

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[1] Stankey, George H. [n.d.] Rationing wilderness use: visitor evaluation of use control in the San Gorgonio and San Jacinto Wildernesses, California. Unpubl. rep., USDA For. Serv., Intermt. For. and Range Exp. Stn., Missoula, Mont.

The advance reservation system would [illegible] alike. Short, numerous trips characteristic [illegible] (Hendee and others 1968; Lucas[1]). Having to [illegible] season would be a problem for many people, particularly, as we pointed out previously, when a high degree of uncertainty surrounds the future. Because of the typical short planning horizon, many wilderness enthusiasts would frequently find their first choice denied.

Selection of rationing techniques should take into account the relative acceptability of the various alternatives to users. In a study of user attitudes toward various control techniques, a reservation system was found to be the most acceptable (Stankey 1973). Forty-three percent of the respondents favored such a system while 39 percent opposed it. These figures, of course, are subject to change with actual exposure to alternative rationing methods.

Rationing by Lottery

A lottery system is a variant of a reservation system. Under a lottery system, visitation rights would be distributed randomly. In many States, certain big-game hunting permits are allocated in this fashion. Individuals seeking a permit might be assigned a number and a drawing equal to the area's carrying capacity would be made. Each individual would have the same probability of success. Operated properly, no individual or group would be favored over another; a lottery, as Hardin (1969) has noted, is "eminently fair."

As was the case with the request system, a lottery would not discriminate among users according to the relative value they place on the wilderness opportunity. Persons who entered the lottery frivolously or to whom wilderness is relatively unimportant would hold the same chance of winning as the wilderness enthusiast. Thus, the suboptimization problem is not eliminated with a lottery.

A lottery would also favor those persons who sought entry to any wilderness rather than persons who sought one particular area. The former group would be able to apply for any of several areas, while the latter group would prefer only one location. However, this situation might help disperse use from heavy-use areas to more lightly used ones, as users consider the relative probabilities of success. This idea has been explored in a recent paper by Greist (1975) in which he suggests the risks [illegible] area, a notion he refers to as "risk zoning." By focusing on the risk of rejection, such a system requires the user to weigh the probability of rejection against the benefits of his desired experience, thus eliminating the efficiency problem normally associated with a lottery.

There is also a problem with "leadtime," or the timespan between an applicant receiving notice of having "won" the lottery and the date of his scheduled visit. A short leadtime discriminates against those visitors requiring long planning horizons and makes it difficult to arrange for alternative activities. But a long leadtime is hard on the spontaneous user.

In most wildernesses, crowding occurs only at certain times or at certain places. For instance, during a recent use season, the Desolation Wilderness in California recorded its highest use on August 8, when nearly 5,000 people were in the area. That

[1] Lucas, Robert C. 1970. Preliminary tabulations--1970 survey of visitors to seven wilderness and related areas in Montana. Unpubl. rep., USDA For. Serv., Intermt For. and Range Exp. Stn., Missoula, Mont.

is almost twice the number of persons in the area on July 22, only about 2 weeks earlier A random selection mechanism would function most smoothly if information were provided as to the probabilities of success as a function of time. If, for example, people were advised that on the basis of previous years' experience, the probability (chance) of obtaining a permit was 1 in 5 for the 4th of June, 1 in 10 for the 4th of July, and 1 in 2 for the 4th of October, people might be expected to weigh the relative advantages of visiting at a specified time against the probability of gaining admission. From this information, then, one would apply for the dates that would maximize the chances of success. If this information were provided, we might expect more even use levels over the season.

A similar system could be used to even out use spatially, either within or between areas. In areas where capacity has always been fully used in the past, the probability of gaining entry would be less than it would be for areas where the capacity was ordinarily underutilized.

A lottery could be extremely cumbersome to administer. For example, a lottery might issue permits for individuals, for groups, or for time. Lotteries that issued permits to individuals would be unpalatable to most visitors because almost all use is in groups. Similarly, lotteries that issued permits to groups would need to account for the variation in group size, so that excessive numbers of individuals did not gain entry. Finally, lotteries that issued permits for time would need to reconcile varying trip lengths in order to prevent use from exceeding an area's capacity.

Although lotteries have been used successfully to distribute permits for big-game hunting, the conditions are different for allocating wilderness-use permits. Duration of big-game seasons is clearly specified in advance, and usually a permit holder may hunt at any time he wishes during that season. To hold use in line with capacity, a wilderness lottery would need to specify when a visit was to occur as well as where.

Wilderness users apparently oppose a lottery as a means of allocating permits to visit wildernesses. Only 18 percent favored a lottery; 62 percent opposed it (Stankey 1973). Many people appear reluctant to leave to chance the opportunity for a wilderness permit. However, because a lottery to allocate wilderness permits is not in use at present, visitor unfamiliarity with the system might contribute to the low level of support.

Rationing by Queuing

Filtering demand through a queue (first-come, first-served or "wait your turn in line" without any provision for advance reservations) is a complex and often misunderstood system of rationing. Queuing actually imposes a price in terms of time. Time pricing has been suggested as preferable to monetary pricing because time is more equally distributed than money (Smolensky 1972). However, available leisure time is not evenly distributed; rather it probably is a U-shaped relationship, relatively more available during youth and old age. Conversely, because leisure time is relatively abundant, its value or opportunity cost is low. While wilderness users are spread across a wide age range, most are found in the 20- to 45-year-old range (footnote 2), where the opportunity costs of time are generally high because of job obligations, income, family responsibilities, etc.

Because time is a price, some of the disadvantages noted for reservation and lottery systems are eliminated; notably the lack of a market that discriminates on the basis of willingness to pay. But queuing also has problems. For example, although the person obtaining the goods or service pays for it in time, no one receives the benefit of the price. When we give up money, our loss is someone else's gain; when we give up time, it is not available to anyone else but is lost forever. Also, this system discriminates against those for whom time has a high opportunity cost. To a considerable

degree, the opportunity cost of time is a function [illegible]
this system, in effect, constitutes a progressive [illegible]
income rises, and thus the opportunity cost of time, so does the cost [tax] of using the facility).

As long as there is competition for the use of the recreational resource base, say for logging or mining, capacity cannot be expanded indefinitely. Further it would be difficult even for Disney to duplicate the vast reaches of, say, the 1.2 million acre Selway-Bitterroot Wilderness. Hence, at zero money price in a situation where demand exceeds supply, the queue filters out users for whom time has a high opportunity cost relative to the value they place on a wilderness experience. Therefore, under queuing, goods supplied publicly at congested facilities are not "public goods" in the Samuelson sense, but goods whose price is a function of the opportunity costs of time rather than money.

Because queuing would benefit persons with abundant leisure time (or low opportunity cost for their time), groups such as students (currently, a major use group) would be favored, while those with little leisure time (a high opportunity cost for time) such as professional-technical people, another major use group, would be penalized. It would also favor local users over those from more distant locations because "locals" would face smaller risks of lost time and money from being turned away.

A queuing system could impose substantial administrative costs. Because many people will choose to "wait in line," services and facilities will need to be provided, including camping areas, garbage collection, and sanitary facilities. Some State Park and National Park campgrounds have waiting or overflow areas. Such areas can be an administrative headache.

Queuing as a method for rationing wilderness use does not appear to have a great deal of support. In the study of attitudes about control, only 28 percent favored a first-come, first-served system, while 57 percent opposed it (Stankey 1973). It might be that the high degree of uncertainty associated with such a system ("Will we be able to get a permit after traveling all this way?" or "How long will we have to wait?") is responsible for the relatively low level of support.

Rationing by Price

The President's Advisory Panel on Timber and the Environment (1973) has recommended that charges be levied for wilderness use, as a means of holding use within the carrying capacity of these areas. Regulating demand through pricing is, of course, one of the most common forms of rationing in our society today. When the idea is applied to wilderness, however there is considerable resistance. Two basic reasons appear to underlie these objections.

First, people object to paying for what has always been free, or for what appears to have been free. However, when use exceeds capacity, costs are unavoidable. The choice is not *whether* to pay, but *how*. Society can choose to "pay" through the diminished quality of the wilderness resource and the experiences it produces, or it can "pay" by selective exclusion from rights to access. Rationing systems are systems for selection, and pricing selects against those *unable* or *unwilling* to pay. Preferably, the rationing system would filter those *unwilling* to pay because they do not place a high relative value on wilderness.

Moreover, we do have precedents for public reaction to the pricing of a traditionally free resource. Participation in hunting as well as many forms of outdoor recreation (e.g., car camping) is now charged for and this is accepted by most people. Occasionally, the costs are high; nonresident fees for hunting exceed $100 many places. What might be critical for obtaining public support is the understanding that the money spent to gain access is used to protect and manage that particular location. For

example, McCurdy and Miller (1968) found that a majority of visitors to a National Wildlife Refuge favored user-fees *if* the revenues were returned to that refuge for maintenance and facility development. Under current Federal regulations, entrance fees cannot be used in this manner (they are returned to the U.S. Treasury). If such earmarking of funds were permitted, support of pricing as a rationing technique might grow.

A second concern about pricing is that a fee, if high enough, would unduly discriminate against the poor. The concern about discriminating against the poor is, in a sense, paradoxical. Wilderness is often said to be available only to the well-to-do because of the high costs thought to be associated with its use. However, studies of wilderness users suggest that per-person, per-day expenditures are generally quite low (Stankey 1971; footnote 2).

The income distribution of wilderness users generally resembles that of the population as a whole. For instance, in a study of users to seven areas in Montana, the income distribution of users was found to be virtually identical to that of the national population (footnote 2). However, there is also evidence of a bimodal distribution of users according to occupation, with about one-third in professional-technical occupations and another one-fourth students. In the above mentioned study, about 25 percent of the users reported incomes under $7,000.

In a recent paper, Vaux (1975) reports that with the exception of students, he found a disproportionately small number of low-income people in four randomly sampled wildernesses in California. And, he argues, students tend to understate their income, reporting their own earned income rather than that of their parents. In his study, 57 percent of the users reported incomes in excess of $10,000 as opposed to 41 percent of the State population and 37 percent for the Nation.

Krutilla and Knetsch (1970) have argued that because of the generally high income distribution of wilderness users, the normal concern with "distributive justice" is less appropriate. Thus, pricing represents a reasonably equitable mechanism for establishing an equilibrium between supply and demand. However, as we have seen, the actual distribution of income groups appears to be fairly wide; low-income groups are represented to a significant degree and we must be concerned with the possible discriminatory implications of a rationing system based solely on pricing.

Beyond the discriminatory shortcomings of pricing, an additional problem concerns the extent to which price could be used to "fine tune" demand. In other words, as the level of use approaches an area's capacity, could a gradual increase in prices keep demand below capacity? (This issue is based upon two assumptions: (1) that we possess accurate knowledge of an area's capacity and can regulate use through other means, and (2) that we understand the relationship between the demand for wilderness at the various price levels that might be assigned.) The three systems discussed earlier all permit exact regulation of use; pricing is a manipulative, rather than a direct control device (Gilbert and others 1972).

There appears to be substantial resistance to the rationing of wilderness through pricing. About one-half of the visitors in an earlier study opposed the imposition of a fee; however, one-quarter favored such a move (Stankey 1973). Although Americans accept market allocations in most areas, there is a strong cultural notion affirming that the opportunity to experience nature should be "free" to the user. This, of course, is not to imply that because the experience has no "cost," it is valueless.

An increasing proportion of choice private lands have hunting rights allocated by pricing mechanisms. Participation in many other recreational activities is regulated by price. Perhaps after more exposure to this system, together with the fading of the initial shock associated with the suggestion of pricing wilderness, resistance will decline.

The primary value of pricing is that it re[illegible]. As the price increases, the quantity demanded diminishes. Because a market is present, problems of nondiscrimination among users based on relative value (problems found in reservation and lottery systems) are reduced. Pricing is a highly flexible system. For instance, it would permit weekly or seasonal fluctuation in use to be evened out by corresponding fluctuations in price. Thus, there could be high prices at peak periods, with low prices, or no prices, at low-use periods.

The system has the further advantage of providing inexpensive, immediate, and fairly accurate information on user preferences. Because actual behavior is an important measure of preference, we should be able to extract the relative values assigned to various activities by different users, based on prices they are willing or unwilling to pay. Also, a user is assured access if he pays, so he can travel long distances without worry.

Finally, imposing a dollar fee to ration use allows the price of the rationing program to be captured rather than lost as is the case with time pricing.

Rationing by Merit

The capacity of a wilderness could be allocated by requiring applicants to demonstrate knowledge and skill. In many ways, merit is the oldest rationing scheme. In a 1940 *American Forests* article, Wagar noted that "nature once certified outdoorsmen." Those who were unequipped, underskilled, and foolish simply did not return from the wilderness. Because modern transportation and improved equipment made access to the wilderness increasingly easy, there was a need, Wagar argued, to develop programs to certify outdoorsmen. Those achieving the appropriate level of skill and knowledge would be "safe to leave in the woods" (Wagar 1940).

To be useful as a rationing technique, a merit system would have to rely upon more than a simple requirement of physical prowess. As Robinson (1975) argues, the reasonably rigorous enforcement of wilderness standards already results in the exclusion of many people. The problem of what to do with the remaining people who still "make it" remains. Moreover, a merit system that functions solely on the basis of physical fitness suffers from serious normative problems. There is no clear basis for assuming that a person in good physical shape is more deserving of an opportunity to visit wilderness than his flabby neighbor. As Robinson notes, "What is the 'merit' of physical vigor?"

The demonstration of skill and knowledge is a fairly common prerequisite in our society for a variety of enterprises; for example, driver's licenses. But more to the point of this paper, such demonstrations are already being used for such things as whitewater river running. Hunter safety programs, now mandatory in 18 States, requires persons 12 to 18 years of age to complete an approved course of instruction in safety and marksmanship before obtaining a hunting license. In many European countries such as Germany, hunting is tightly controlled through a thorough program of instruction in gun handling, ethics, safety, and wildlife biology. All are examples of the use of merit as a means of access to a resource.

The merit system is founded on the notion that improved behavior will reduce impact Its focus would be upon reducing the per-unit impacts of use so that, conceivably, higher levels of use would be possible. It also assumes that much of the behavior that currently creates undesirable resource impacts or conflicts with other users results from innocently uninformed, rather than malicious, behavior. For example, nearly two-thirds of the users to seven western Montana wildernesses and backcountry recreation areas reported that burying their noncombustible trash was the appropriate way to dispose of it, despite Forest Service efforts to promote a "pack it in, pack it out" program (footnote 2). Thus, by supplying factual information, much undesirable behavior could probably be reduced.

A merit system could perform three important functions in holding use consistent with capacity. First, as we discussed above, it could reduce per capita impact, thereby possibly postponing the need for other more direct restrictive actions. Second, the numbers of visitors wanting to visit wilderness could be restricted by means of raising the minimum "score" required to obtain entry. Third, the presence of a system demanding time and effort on the part of the individual desiring entry imposes an important "cost" that is paid through the willingness of that individual to gain the necessary qualifications. Thus, merit meets an important criterion as a wilderness rationing device; namely, it places a positive relationship on the value of the opportunity and the behavior required to achieve that opportunity.

A merit system might also increase the enjoyment and appreciation that participants derive from wilderness. Understanding the complexity of the natural surroundings and being able to live in concert with the environment might add substantially to the values enjoyed by users.

There might be opportunities for cooperative training programs developed by the wilderness management agencies in conjunction with some of the major outdoor recreation, educational, and conservation clubs. Approved courses for instructors could perhaps be developed in order to make the program available to as many people as possible. Initially, it might be possible to contact people about the new requirements through such sources as outdoor recreation and conservation groups or through lists of names from wilderness permits now required in some areas.

Substantial practical problems exist with the merit system. It would be necessary to determine desired behavior. For instance, it is not yet clear what method of disposing of human waste is best; the best method probably varies as one moves from the Oregon Cascades to the Grand Canyon of Arizona. Ways of accurately testing knowledge could be difficult to develop. Settling upon who should establish the standards for entry would be controversial. Determining the appropriate level of knowledge or ability would also have to be reconciled. Finally, developing procedures, personnel, and facilities to carry out such tests would be an awesome task.

Demonstration of merit could be interpreted as being discriminatory against those people who are physically handicapped or of such age they cannot meet the minimum standards (Hardin 1969). However, some modest level of skill and knowledge is necessary for any wilderness visit, regardless of whether one has to demonstrate their ability to gain access or not. The system could also lead to charges of being "elitist," that wilderness was available to only the young and the strong. To the extent that alternative opportunities catering to the handicapped or the elderly are not provided, these latter charges would be difficult to refute.

Generally, merit systems have been founded on a safety criterion. To use merit as a means of limiting use in wilderness, it would be necessary to demonstrate that its implementation is more than another bureaucratic hassle; that it will provide benefits to users. If such a system could in fact lower per capita impact, the time at which more authoritarian rationing might become necessary could be postponed, a situation most users would probably favor.

A SUMMARY OF IMPACTS

A number of criteria for evaluating each of the rationing systems can be specified. Depending upon the criteria chosen, the system which is "best" in any given situation will probably differ. In table 1, we have summarized the probable impacts of each system in light of eight selected criteria. These criteria include such things as the user groups most affected (adversely and beneficially), current administrative experience with the system, acceptability to users, difficulty of administration, efficiency, the principal way in which use impacts are controlled, and how each system affects user behavior. These criteria are by no means the only relevant ones, but they provide the basic information to help managers judge the system they should use.

		Evaluation Criteria		
		Client group adversely affected by system	Experience to date with use of system in wilderness	Acceptability of system to wilderness user
(Reservation		Those unable or unwilling to plan ahead; e.g., persons with occupations that do not permit long-range planning, such as many professionals.	Main type of rationing system used in both National Forest and National Park wilderness.	Generally high. Good acceptance in areas where used. Seen as best way to ration by users in areas not currently rationed.
	group benefited. Those	No one identifiable group discriminated against. Can discriminate against the unsuccessful applicant to whom wilderness is very important.	None. However, is a common	
(First-come	Those with low opportunity cost for their time (e.g., unemployed).	Those persons with high opportunity cost of time. Also those persons who live some distance from areas. The cost of time is not recovered by anyone.	Used in conjunction with reservation system in San Jacinto Wilderness. Also used in some National Park Wildernesses.	Low to moderate.
Pricing	Those able or willing to pay entry costs.	Those unwilling or unable to pay entry costs.	None.	Low to moderate.
Merit	Those able or willing to	Those unable or unwilling to invest time and effort to meet requirements.	None. Merit is used to allocate use for some related activities such as river running.	Not clearly known. Could vary considerably depending on level of training required to attain necessary proficiency and knowledge level.

	Evaluation Criteria			
	Difficulty for	Efficiency - extent to which system can minimize problems of suboptimization	Principal way in which use impact is controlled	How system affects user behavior[2]
Request (Reservation)	Moderately difficult. expanded hours. Record keeping can be substantial.	Low to moderate. Under utilization can occur because of "no shows," thus denying entry to others. Allocation of permits to applicants has little relationship to value of the experience as judged by the applicant.	Reducing visitor numbers. Controlling distribution of use in space and time by varying number of permits available at different trailheads or at different times.	Affects both spatial and temporal behavior.
Lottery	permits over an entire use season could be very	Low. Because permits are assigned randomly, persons who place little value on wilderness stand equal chance of gaining entry as those who place high value on opportunity.	Reducing visitor numbers. Controlling distribution of use in space and time by number of permits available at different places or times, thus varying probability of	Affects both spatial and temporal behavior.
(First-come	Low difficulty to moderate. Could require development of facilities to support visitors wait-	Moderate. Because system rations primarily through a cost of time, it requires some measure of worth by participants.	Reducing visitor numbers. Controlling distribution of use in space and time by number of persons permitted to enter at different places or times.	Affects both spatial and temporal behavior. User must consider cost of time of waiting in line.
(Fee)	Moderate difficulty. Possibly some legal a fee for wilderness entry.	Moderate to high. Imposing a fee requires user to judge worth of experience against costs. Uncertain as to how well use could be "fine tuned" with price.	Reducing visitor numbers. Controlling distribution of use in space and time by using differential prices.	Affects both temporal and spatial behavior. User must consider cost in dollars.
Merit (Skill and knowledge)	Difficult to moderately difficult. Initial investments to establish licensing program could be substantial.	Moderate to high. Requires users to make expenditures of time and effort (maybe dollars) to gain entry.	Some reduction in numbers as well as shifts in time and space. Major reduction in per capita impact.	Affects style of user's behavior.

[1] Based upon actual field experience as well as upon evidence reported in visitor studies (Stankey 1973).

[2] This criterion is designed to measure how the different rationing system would directly impact the behavior of wilderness users (e.g., where they go, when they go, how they behave, etc.).

MANAGEMENT IMPLICATIONS

As contradictory to the idea of wilderness [illegible] ness use will become increasingly common. In our judgment, this will be necessary if the significant ecological and social values of such areas are to be fully protected.

At the same time, we are concerned that rationing might be adopted because it appears to be administratively more convenient than other measures. Similarly, rationing decisions made in response to problems that are more imagined than real, or that are based on highly localized or temporary problems, could lead to public opposition to rationing as a legitimate management tool.

Sound management principles are the most effective safeguard against such problems. We particularly endorse two principles that, will help insure the appropriate and legitimate use of rationing. First, we advocate the control of the environmental expense of use rather than use per se (Lucas 1973; Hendee 1974). That is, we should be primarily concerned with reducing the physical and social [illegible] associated with use rather than simply cutting back on use itself. This is an important distinction; not all kinds of wilderness use create similar levels of impact. A good example, with all else being equal, is the relative ecological impact created by one backpacker as opposed to one visitor on horseback. Moreover, use by itself is a fairly poor predictor of impact (Wagar 1964). Variables such as method of travel (Lucas 1964), season of use (LaPage 1967), and habitat type (Helgath 1975) seem more critical elements in the equation of predicting impact.

From a management perspective, this principle suggests that we develop measures of the relative impacts of different styles of wilderness use so that logical decisions regarding use restrictions can be implemented. Those uses that are more destructive or consumptive than others should be the first ones restricted. By focusing on eliminating unwanted impacts rather than indiscriminately cutting use, the time when direct rationing would be appropriate can probably be postponed.

A second tenet we might label as the principle of minimum regimentation. We have already discussed the fact that for many people, the wilderness experience is an opportunity for freedom and spontaneity. Restrictions and regulations obviously intrude on this experience. Consequently, we endorse management programs that use only that level of regulation necessary to achieve preservation objectives (Lucas 1973). For example, if a program informing visitors about current use distributions is sufficient to change use patterns in a desirable fashion, then it would be inappropriate as well as unnecessary to impose more heavy-handed measures, such as directly controlling where people can go.

A rough continuum of use-control measures can be outlined, specific actions ranging from subtle, light-handed techniques such as providing information to users, to authoritarian actions accompanied by sanctions, such as mandatory permits, with fines imposed for noncompliance. Gilbert and others (1972) distinguished between what they label as "manipulative" measures that influence behavior by controlling the

factors that influence decisions about where to go or how long to stay, and "regulatory" measures that directly control when, where, or how people may use an area. Both types of control are legitimate, but their appropriateness must be determined in light of specific conditions.

These principles help bring the issue of rationing into perspective. We would like to repeat ourselves: rationing is a management option, that, when used in the appropriate conditions, is both legitimate and useful. Under such conditions, it should be used without apology and in full confidence that where a rational explanation for its need exists, public support and understanding can be expected. Lucas (footnote 2) reports that about three out of four visitors to seven Montana areas supported the idea of restricting use if an area was being used beyond capacity. Stankey (footnote 1) found that 80 percent of sampled visitors in the San Gorgonio and San Jacinto Wildernesses, where rationing is now in effect, agreed that such a measure was necessary. Fazio and Gilbert (1974) also found strong support for the rationing program instituted in Rocky Mountain National Park, with 80 percent of those who did not get a permit indicating that such a program was necessary.

SOME GUIDELINES FOR RATIONING WILDERNESS USE

The five rationing systems we have reviewed represent different techniques for accomplishing a similar objective; holding use at a level consistent with the preservation of natural ecological processes and the opportunity for a primitive, low-use intensity recreational experience. Each system offers certain advantages to accomplishing that objective; each has its drawbacks. In choosing when to ration and how to do it, certain guidelines can be used that we believe will aid managers in making good decisions.

Guideline 1: An Accurate Base of Knowledge Is Necessary

As with all other forms of resource management, the availability of good information about wilderness and its use is a prerequisite to using rationing effectively as a tool. First, as we suggested earlier, it is important that rationing be instituted in response to real problems; not to imaginary problems or to temporary problems. Solid data, not impressions, are required. Certainly one of the major advantages of the mandatory wilderness permit system now in effect in over 40 National Forest wildernesses and in many national park backcountry areas is that it provides an accurate record of use and of developing trends, permitting a much improved assessment of conditions (Lime and Buckman 1974). Systematic monitoring of physical-biological conditions, or the careful analysis of records kept by wilderness managers would provide additional information for managers. Such information is absolutely necessary to identify problem areas, their precise nature, and alternative solutions.

Second, it is important that managers know something about who the users are and what kind of use they make of the wilderness. Because alternative rationing measures impose different kinds of costs on different kinds of users, a knowledge of the clientele could head off implementation of a measure that might severely affect some users. For instance, a fee system might greatly restrict the ability of students, a major use group, to gain access. Similarly, a lottery allocating a place in time might make use excessively difficult for persons whose schedule is highly uncertain more than a week or so ahead.

Guideline 2: Use Direct Rationing Only When Less Restrictive Measures Fail

guideline.

Guideline 3: Combination of Rationing Systems Will Help Minimize Costs

There are no cost-free solutions in rationing. Each technique imposes certain systematic costs that will be felt by users and managers alike. Usually, certain groups will be affected by one system more than another. Thus, the issue before managers is not one of preventing costs from occurring, but rather, one of minimizing the costs that will be inevitable.

Because of the differential costs of the five rationing systems, and the need to minimize these costs, it will usually be necessary as well as desirable to develop combinations of rationing systems. One good example of such a combination is found in the San Jacinto Wilderness. Here, 75 percent of the daily capacity is allocated through a request system, with requests being filled on a first-come, first-served basis by mail, phone, or in person. As we noted earlier, the disadvantage of the request system is that it can lead to underutilization of a facility through "no-shows." Additionally, it discriminates against those persons not able (or willing) to plan ahead. To offset these problems, the remaining 25 percent of the daily capacity in the San Jacinto is allocated through a queuing system, and is assigned only on that specific day. In this way, drop-ins are afforded an opportunity to obtain a permit.

On the Mt. Whitney trail, 100 percent of the daily capacity is allocated on a request basis, but the high percentage of "no shows" (40 percent in 1974 and 50 percent in 1975) allows administrators to accommodate almost all other persons arriving without a permit on a first-come, first-served basis.

In the Boundary Waters Canoe Area, overnight use is now regulated by a request system. Twenty-five percent of the permits for any given period are allocated by a long-term reservation system to accommodate those who can plan ahead and/or travel long distances to reach the area. The remaining 75 percent of the permits are allocated on a short-term reservation system (really a queuing system) to handle the more spontaneous users. The relative proportion of permits assigned to these two systems was based on an analysis of past use records, so that officials felt confident that the availability of permits was in accord with demand. Such information confirms the importance of our first guideline emphasizing the need for an accurate base of information.

Officials in the BWCA also considered the imposition of a $5 deposit on advance reservations, refunded on arrival to pick up the permit, in order to reduce the problem of "no shows." Although this was dropped because of uncertainty of its legality, it was an imaginative suggestion that might have been quite effective.

Multiple rationing systems are also in effect in several National Park backcountry areas, generally involving a combination of request and queuing systems.

Queuing might also represent an important complementary system in conjunction with a pricing system. For the many present day wilderness visitors who possess higher incomes, a fee would not be discriminatory because those rationed out would be primarily those who placed a higher value on alternative uses of their money. In other words, it would not be a matter of inability to pay that rationed these people out, it would be a matter of willingness. This is how an efficient rationing system should operate. But there are clearly others who would be willing but unable to pay the price. For instance, students and low-income people would be discriminated against by a fee set at a level sufficient enough to reduce use. However, time generally has a low opportunity cost for many of these people. By implementing a queuing system in conjunction with a fee system, users could choose to pay by money or by time.

We should also point out that each system is capable of flexible application. For instance, the imposition of a fee does not necessarily mean one price for all locations. In fact, differential pricing to alter use patterns would appear to be a more appropriate action. Also, to counter problems of discriminating against those willing but unable to pay, subsidies might be available to certain individuals.

There are certainly difficult questions about rationing for which no clear answers exist. For instance, if a combination of systems is planned, what is the relative proportion of the capacity that should be allocated by each system? In areas where commercial outfitting occurs, how should permits for entry be allocated to the commercial sector; should the same system for private use be utilized or should some special provision for commercial users be developed? Certainly the answer to such questions would rest in knowing the present clientele, as well as the clientele in the near future.

Guideline 4: Rationing Should Require Users to Judge the Relative Worth of the Opportunity

What rationing system is best? Although there are again no pat answers, we can offer this observation. It appears to us that the ideal system or combination of systems should be based on establishing a relationship between the opportunity to visit wilderness and the value an individual places on that opportunity. One of the advantages of pricing is that it clearly requires people to make choices among the possible alternative uses of their money--it makes people "put their money where their mouth is." At the same time, the uneven distribution of income makes pricing an imperfect system. But people can pay in other ways--by time in a queue or by time and personal effort in a merit system. Because wilderness is a scarce resource, it is our belief that rationing should demand a personal assessment of worth on the part of potential participants.

Guideline 5: Rationing Programs Need Monitoring and Evaluation

Although there is evidence that people will support the institution of rationing in wilderness, there is still much uncertainty about its effect on use, how it will alter the wilderness experience, and so forth. Consequently, it seems important that when the decision to ration is made and a particular system or combination of systems is chosen, that a program of monitoring and evaluation also be established. From a simple economic perspective, it seems unwise to invest a high level of money, manpower, and time into the development of what is an inherently controversial program, without also establishing the ability to accurately evaluate performance at a later date. Moreover, because there are only limited data about how rationing might work in wilderness, how people will behave and think of such measures, it seems doubly important that managers have an accurate and systematic source of feedback. Well-designed surveys are important sources of such information but even review by persons running the system would be helpful as long as the information gathered was systematic and as objective as possible.

SUMMARY

Increasing levels of demand on [illegible] objective of preserving the natural ecological [illegible] qualities of wilderness, are making the task of wilderness management increasingly difficult. Managers have a variety of tools to contend with some of these problems, including rationing.

Five basic systems of rationing can be defined: (1) rationing by request; (2) rationing by lottery; (3) rationing by queuing; (4) rationing by price; and (5) rationing by merit. Each system has certain [illegible] associated with it.

Currently there are [illegible] effective tool is a set of principles that allow him to place rationing in the proper perspective as a management strategy. [illegible] pective discussion of each [illegible] ticularly when the [illegible] opportunity. It is important that objective and systematic sources of feedback be established to permit evaluation of rationing programs.

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U S

CHIPPING AND PULPING DEAD TREES OF FOUR ROCKY MOUNTAIN TIMBER SPECIES

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RESEARCH SUMMARY

The vast quantity of dead down and standing timber in the Rocky Mountains is a potential resource for the pulp and paper industry. Pulpwood bolts of dead Engelmann spruce, Douglas-fir, western larch, and lodgepole pine were experimentally chipped and evaluated as pulp material. Samples from dead bolts and green bolts indicated that the dead wood was sound (specific gravities were essentially the same) and that the dead tree bolts had a much lower percent moisture content than the green bolts. As a result of the lower moisture content, 14 to 30 percent more power was required to chip the dead trees than the green trees. Also, chipping the dead wood produced a slightly larger percentage of fines than the chipping of green wood. No problems were encountered in separating the bark from the wood chips. Test runs made with dead lodgepole pine chips indicated that the pulp should be suitable for a variety of paper and board products.

INTRODUCTION

The Rocky Mountain region contains vast quantities of dead down and standing timber that, after many years of exposure to the elements, has suffered little deterioration. The exact quantity of dead timber available is unknown, but estimates place the amount at approximately 3.5 billion cubic feet and this amount is increasing annually as insects and disease continue to take their toll of green timber.

Many of the dead trees are removed from the sale area at the time of harvesting the green timber, but the bulk of this material is left on the area and becomes a part of the logging residue. More intensive use of dead trees would enhance the raw material base of the region's wood-using industry, facilitate management practices on logged-over areas, and help decrease the cost of postharvest cleanup.

One possible method of utilizing dead trees in this region is to chip the wood either in the forest or at the mill, for manufacturing into paper. However, the paper-making industry needs additional information regarding the processing and quality of the resulting chips.

This paper reports the results of two investigations: (1) characteristics of chips from dead down and standing trees, and (2) the pulping characteristics of dead lodgepole pine trees. The studies are discussed separately.

CHIP QUANTITY AND QUALITY

Objectives of this part of the study were: (1) to compare quantities and sizes of chips obtained from green trees and dead trees of the same species; (2) to compare horsepower required to chip various sample bolts; and (3) to determine whether current technology would remove bark from chips produced from dead trees.

Sampling and Processing

Samples of dead down, dead standing, and green trees were selected in a single drainage in western Montana. Each sample consisted of about six 5-foot-long bolts with a maximum diameter of 7 inches, weighing in excess of 100 pounds. The bolts were of sound wood with no obvious decay.

Four species, lodgepole pine, Engelmann spruce, Douglas-fir, and western larch, were included in the sample. These species represent a range in average specific gravity from 0.33 (Engelmann spruce) to 0.48 (western larch) (USDA Forest Service 1974).

At the time the bolts were collected, disks, approximately 1 inch thick, were cut from the tree stem immediately adjacent to the bolt ends. These disks were identified as to tree and bolt and were used for determining specific gravity and moisture content of the sapwood and heartwood.

A total of 60 bolts, 15 of each species, 5 each from dead down, dead standing, and green trees, were individually wrapped in polyethylene to prevent changes in moisture content and to capture bark that sloughed during shipping and handling. The bolts were shipped to the Forest Engineering Laboratory at Houghton, Michigan, for processing.

Just prior to chipping, the samples were unwrapped and any loose bark weighed. All material was chipped by a 48-inch, 3-knife Morbark Chip-pak chipper with the chipper knives being ground just prior to testing. During chipping, the input power was measured by a Hall-effect, three-phase wattmeter transducer (Papworth and Johnson (1968) The output from this transducer was displayed on a single channel of a Sanborn recorder. The total area under the recorded power curve was measured with a compensating polar planimeter to determine total energy consumed during chipping.

Following chipping, representative samples were uniformly mixed and classified to size with a Sweco round-hole screen classifier (fig. 1). Each size class was subsequently weighed and sampled, with the samples being manually segregated to determine percent bark in each size. All analyses were based on dry weights.

Figure 1.--Sweco round-hole classifier for classifying wood chips according to size.

The bark removal methods used were not independent, separate systems, but were variations of one system. The system components used are briefly summarized and coded for reference:

Compression debarking (C).--A processing treatment in which the bark/wood chip mass is passed between two opposed, hydraulically loaded, steel compression rolls placed 0.020 inch apart. Bark generally adheres to the rolls more readily than wood and is scraped from the rolls 180° from point of compression. Screening the chip output removes much of the bark that does not adhere to the rolls, but that has been fragmented by the roll nip action (Arola and Erickson 1973).

Ball milling (B).--Chip output is passed through a specially designed ball mill to further break up any bark not removed by compression debarking for subsequent screening (Mattson 1974).

Steaming (S).--Prior to compression debarking, the bark/chip mass is presteamed for 5 minutes at 30 psi to enhance bark removal.

Air flotation (A).--A processing treatment that removes up to 60 percent of the input material as clean wood chips, leaving the remainder for compression debarking. This process segregates particles having distinct differences in terminal settling velocities due to density, shape, or size (Sturos and Erickson 1974).

To establish final output products after processing, two final screening methods were examined: (1) to include in the output the 3/16-inch size chips which are generally high in bark content but increase wood recovery, and (2) to exclude the 3/16-inch size chips which generally increase bark removal but decrease wood recovery. The latter method is on the assumption that the rejected material will be utilized for other products or for fuel. Although bark removal from green chips was not intended to be part of the study, results are included to provide additional information on western species (Arola and Host 1976; Hillstrom 1974).

Results and Discussion

Specific Gravity and Moisture Content

Average specific gravity and moisture content are shown in table 1. In general, the specific gravity values approximate the published values for the different species and, as expected, there were only small differences between the values for the dead and green trees. The differences between the sapwood and heartwood determinations can, perhaps, be attributed to the extractive content present in the heartwood.

The moisture content of the sapwood of the green bolts was much greater than the moisture content of the heartwood. This agrees with published information (USDA, Forest Service 1974). For the dead trees, the sapwood had a lower moisture content than the heartwood. This, too, is as expected because the sapwood is more exposed than the heartwood and hence would dry more rapidly. The bolts from the green trees had a much higher moisture content in both sapwood and heartwood than the bolts from the dead trees. The dead down trees had slightly higher moisture content than the dead standing trees. Undoubtedly, the down trees absorbed some moisture from the ground and were, in addition, shaded and protected by herbaceous plants from the direct influence of the elements.

Horsepower Requirements

Horsepower requirements for chipping dead and green wood of the four species are listed in table 2.

Table 1.--*Average percent moisture content and specific gravity of samples taken from the ends of the sample material*[1]

Species	Condition	Average percent moisture content		Average specific gravity[2]	
		Sapwood	Heartwood	Sapwood	Heartwood
Lodgepole pine	Green	114	50	0.37	0.38
	Dead standing	16	18	.42	.42
	Dead down	21	27	.34	.35
Douglas-fir	Green	112	29	.41	.49
	Dead standing	14	15	.40	.43
	Dead down	18	26	.34	.37
Engelmann spruce	Green	97	40	.33	.37
	Dead standing	19	27	.36	.37
	Dead down	22	28	.37	.41
Western larch	Green	104	41	.42	.41
	Dead standing	13	13	.44	.42
	Dead down	21	29	.37	.42

[1] Each value is the average of at least four determinations.
[2] Based on green volume and ovendry weight.

Table 2.--*Horsepower requirements for chipping three types of wood of four different species*

Species	Hp-min per ft^3[1]			Percent increase
	Dead down	Dead standing	Green	$\frac{\text{Ave. dead}^2 - \text{green}}{\text{green}} \times 100$
Lodgepole pine	[3]285.17	272.00	214.54	29.85
	(19.3)	(10.4)	(8.7)	
Douglas-fir	252.38	238.43	214.86	14.22
	(19.3)	(25.4)	(7.6)	
Engelmann spruce	275.20	220.01	189.82	30.44
	(14.1)	(12.3)	(3.5)	
Western larch	205.67	237.18	186.92	18.46
	(23.0)	(9.6)	(12.3)	

[1] To convert $\frac{\text{hp-min}}{ft^3}$ to $\frac{\text{hp-h}}{\text{cord}}$ multiply by 0.022222.

To convert $\frac{\text{hp-min}}{ft^3}$ to $\frac{\text{Joules}}{m^3}$ multiply by 0.026345.

[2] Includes both dead down and standing
[3] Mean with std. dev. in parentheses.

The total energy required to chip the various types of wood was analyzed using the analysis of variance method. The results of this analysis showed a significant difference, at the 95 percent confidence level, in the energy required to chip dead wood as opposed to green wood for all species. However, there was little difference when comparing energy required to chip dead standing with dead down wood. Lodgepole pine (dead down) required the greatest amount of energy at 285.2 horsepower minutes per cubic foot (hp-min/ft^3) compared to green lodgepole at 214.5 hp-min/ft^3. The largest differences occurred with Engelmann spruce and lodgepole pine where approximately a 30 percent increase in power was required to chip dead wood compared to green wood.

The differences in power requirements can probably be attributed to the differences in moisture content. Apparently the moisture in wood acts somewhat like a lubricant and reduces the energy required to chip or saw green wood (Quelch 1964).

Chip Size and Composition

Chip size.--Differences in chip size classes within species and between conditions was not as marked as expected (fig. 2, 3, 4, and 5), with only a slight increase in fines occurring between green and dead. Overall chip quality was good, with more than 75 percent of the chips falling in the -1-1/8 to +3/8 category in all cases.

Bark removal.--Many of the dead wood samples either did not contain any bark before shipping, or lost much of their bark in shipping and handling. Therefore, the majority of chipped samples did not contain enough residual bark to require processing.

The data for these species were:

Douglas-fir (dead standing)	0.35
Douglas-fir (dead down)	.23
Lodgepole pine (dead standing)	2.46
Lodgepole pine (dead down)	.53
Engelmann spruce (dead down)	.19
Western larch (dead standing)	1.58

Of the material tested, with the exception of Douglas-fir, excluding the 3/16-inch chips from the output increased bark removal but decreased the amount of wood fiber recovered (table 3). Douglas-fir bark, because of its physical nature, is not easily fragmented by the roll nip action, therefore introduces larger bark particles into the final output. Consequently, rejection of the 3/16-inch size chips, the most bark-free chip size for Douglas-fir, increased bark content and decreased the percentage of wood in the final output. In contrast, excluding the 3/16-inch chips from the western larch (dead down) output reduced final bark percentages by over one-half, with little effect on wood recovery. In all cases except for Douglas-fir, with selection of the proper output, residual bark is less than 4 percent, with at least 95 percent of the original wood fiber recovered.

Although we had trouble debarking green Douglas-fir chips, a pressurized bench top device (Plahutnik 1973) showed promise for segregating clean chips from barky chips. When sufficient pressure is applied to a floating chip, water is forced into the intercellular spaces, causing the chips to sink. If the wood and bark behave differently under pressure, segregation occurs.

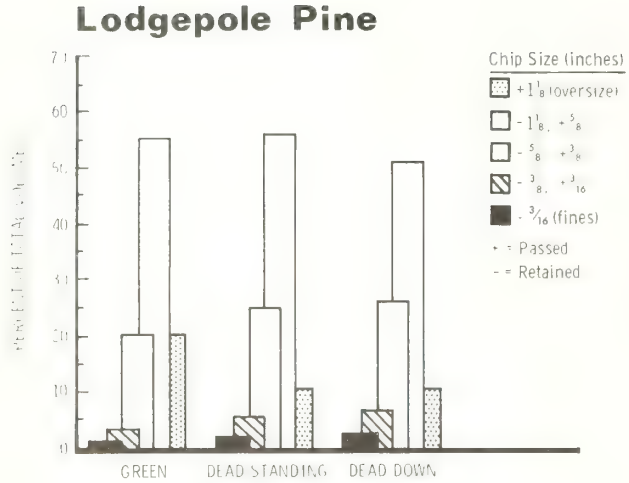

Figure 2.--Distribution of green, dead standing, and dead down lodgepole pine pulp chips according to size.

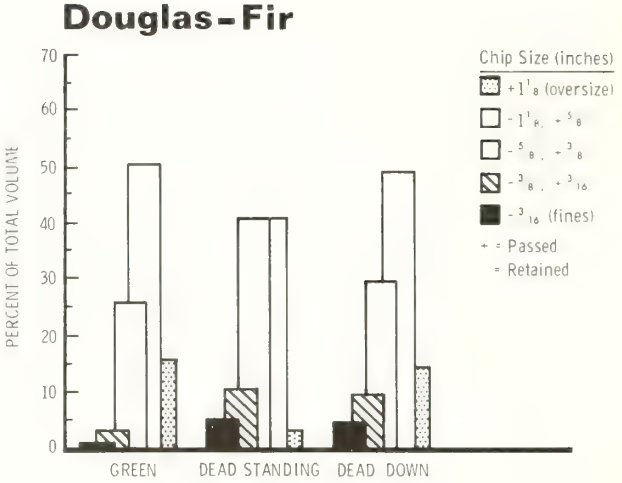

Figure 3.--Distribution of green, dead standing, and dead down Douglas-fir pulp chips according to size.

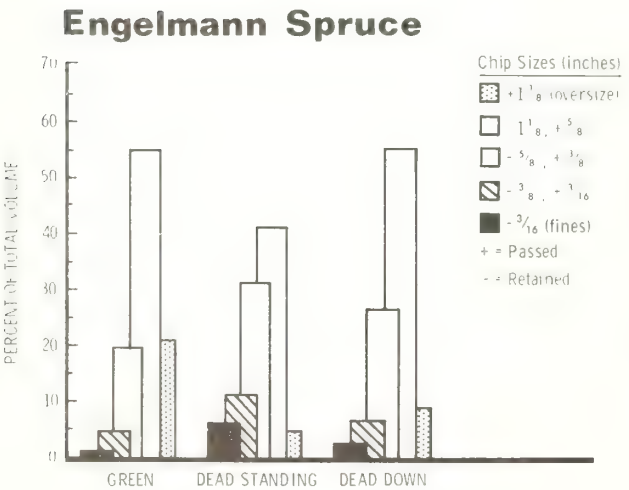

Figure 4.--Distribution of green, dead standing, and dead down Engelmann spruce pulp chips according to size.

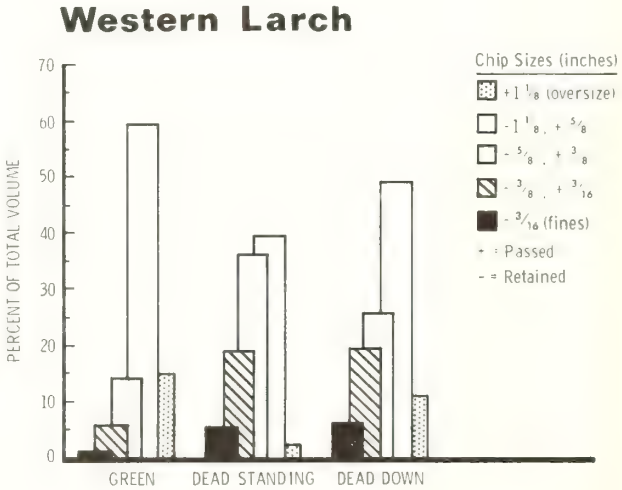

Figure 5.--Distribution of green, dead standing, and dead down western larch pulp chips according to size.

Table 5.

Species	Condition	Bark removal process	Bark in output	Output in			Output	Bark	Wood
Lodgepole pine	Green	SCB		1.0	87.2		0.3	96.7	75.1
Douglas-fir	Green	SCB	15.7			97.5	9.8		
Engelmann spruce	Green	AC	13.4	4.1		98.8		72.4	
Engelmann spruce	Dead standing	ASC	1	1.9	86.7		1.6	89.8	
Western larch	Green	SCB	14.		76.5	95.2			
Western larch	Dead down	ACB				99.1			

[1]Bark-chip separation methods coded as follows: and A - air flotation.

[2]Based on sample weights.

PULPING DEAD LODGEPOLE PINE

Sample Collection and Pulping

In the second part of the study, a sample of lodgepole pine was collected and shipped to the Forest Products Laboratory at Madison, Wisconsin, for pulping tests. The sample material consisted of 15 bolts, 4 feet long, obtained from insect-killed trees near Missoula, Montana. The trees had been dead for at least 7 years, with no decay and little bark.

At the laboratory, the bolts were chipped and the chips were subjected to two pulp digestions. After the digestions, the pulp and few sample handsheets prepared from the pulp were evaluated according to Technical Association of Pulp and Paper Industry (TAPPI) Standards (table 4).

Table 4.--*Properties of kraft pulp made from dead lodgepole pine (source of tests and terms--Technical Assoc. Pulp and Paper Industry)*

Test number	Digestion number	Test	Freeness 600	500	400	300
25356	5904-X	Burst factor	102.0	111.5	115.5	117.5
Yield = 52.8%		Tear factor	108.0	97.5	90.0	89.5
Kappa = 78.3		Breaking length - M	13,850	14,600	14,900	15,000
		Density - G/cc	0.63	0.68	0.71	0.74
		Beating Time - Min	44	62	75	85
25357	5903-X	Burst factor	99.0	109.0	114.0	117.0
Yield = 46.7%		Tear factor	117.5	95.0	90.0	88.0
Kappa = 34.6		Breaking length - M	13,900	14,850	15,350	15,600
		Density - G/cc	0.68	0.73	0.75	0.76
		Beating Time - Min	19	30	39	47
25357-A	5903-X	Burst factor	96.0	107.0	112.0	113.0
	Bleached 6792	Tear factor	118.0	101.0	94.5	91.0
	CEDED	Breaking length - M	12,550	13,850	14,500	14,800
		Density - G/cc	0.72	0.76	0.77	0.79
		Beating Time - Min	10	18	25	30

The pulping and bleaching characteristics of the dead lodgepole pine were quite satisfactory. The yield for the bleached pulp was 46.7 percent and for the linerboard 52.8 percent (table 5). The pulp properties, also, were exceptionally good and about the same as that obtained from green wood of this species (typical of the species having low density wood and slender fibers). The quality of these properties is shown by high burst and tensile strength and low tearing resistance of the handsheets. Apparently the long exposure of the trees had little effect on quality of pulp.

Table [illegible] -- [illegible] pine pulp chips (source of tests and terms--Technical Assoc. Pulp and Paper Industry)

Digestion 5903-X (For bleaching)	17.51% active alkali, 25.0% sulfidity L/W = 4/1 90 min 80-170°, 90 min at 170°C.
	Spent liquor 8.4 g/l Na_2S (Na_2O) 6.2 g/l NaOH (Na_2O)
	Yield Total 46.7% Scr. 0.9% (0.012 inch)
	Kappa No. = 34.6
	Bleaching: C - Cl_2 - [illegible] Brightness = 89.2% E - NaOH - 2% D - ClO_2 - 0.76% E - NaOH - 1% D - ClO_2 - 0.38%
Digestion 5904-X (For linerboard)	15.0% active alkali, 25.0% sulfidity L/W = 4/1 90 min 80-170°, 45 min at 170° C.
	Spent liquor 7.0 g/l Na_2S (Na_2O) 4.5 g/l NaOH (Na_2O)
	Yield Total 52.8% Fiberized in 8-inch Bauer
	Kappa No. = 78.3

Results and Discussion

The results of this limited study indicated that, as in the previous study, chipping dead wood produced a higher percentage of fines than chipping green wood. Some of these fines might be salvaged, if suitable digestion equipment is available. Chip yield was as follows:

	Kg(wet)	*Pct*
Bolts	81.90	
Fines (passed through 1/4-inch screen)	6.60	8
Oversize (retained on 1 1/4-inch screen)	1.58	2
Accepts	73.72	90

CONCLUSIONS

Studies indicate that standing and down dead Engelmann spruce, Douglas-fir, western larch, and lodgepole pine trees can be chipped satisfactorily. Because of the lower moisture content in the dead trees a significantly greater amount of power was required to chip the dead than the green trees. Depending on the species, this increased power varied from approximately 14 to 30 percent. The dryness of the wood also affected the percent of fines (unusable wood chips) produced. Chipping dead trees produced a slightly larger percentage of fines than chipping green trees.

Separating bark from wood chips should present no major difficulty. Sample bolts from the dead trees had lost most of their bark during handling and shipping. Similar bolts for a commercial operation would probably arrive in the same condition with large amounts of the bark either sloughed or knocked off.

No problems were encountered in pulping dead lodgepole pine. Experimental digestions and evaluation of the pulp and handsheets indicated that the material could be used for the manufacture of both bleached and unbleached pulps suitable for a variety of paper and board products. The quality difference between these pulps and pulps made from green lodgepole pine wood was insignificant.

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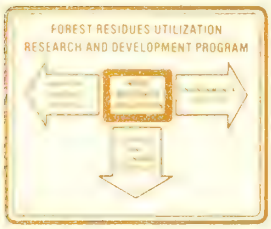
FOREST RESIDUES UTILIZATION
RESEARCH AND DEVELOPMENT PROGRAM

WOOD PRODUCT POTENTIAL IN MATURE LODGEPOLE PINE STANDS.

Bitterroot National Forest

ROBERT E. BENSON
RICHARD A. STRONG

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WOOD PRODUCT POTENTIAL IN MATURE LODGEPOLE PINE STANDS, BITTERROOT NATIONAL FOREST

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The Bitterroot National Forest contributed substantially to this report in the form of resource data, consultation, and review of earlier drafts.

The Bitterroot Resource Conservation and Development Committee provided guideline questions, and encouragement through many meetings and discussions of the wood resource and its potential contribution to the Bitterroot economy.

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RESEARCH SUMMARY

Mature lodgepole pine stands in Montana's Bitterroot National Forest could yield 1.2 to 2.3 million cubic feet of wood annually. Three-fourths of this volume is suited for high value roundwood products. About 15,000 houselogs, 62,000 corral rails, and 110,000 fenceposts, plus one-fourth million cubic feet of fiber material could be harvested from land classed as "standard"--suitable and available for harvest. Additional volume could be obtained by salvage-cutting of dead timber.

Rapid growth in the past few years of plants using lodgepole roundwood products has created a brisk demand for lodgepole. Harvest of dead lodgepole increased tenfold from 1966 to 1975. However, much of the lodgepole resource is not accessible by existing roads and will require careful harvest to protect other resource values, particularly in high elevation fragile areas.

The lodgepole pine resource could provide employment to small logging operators or part-time loggers, particularly if a convenient market outlet such as a concentration yard were developed.

Increased use of lodgepole in the Bitterroot depends on location of the stands, economic conditions, harvesting technology and feasibility, and the level of harvest allowed in land management plans.

INTRODUCTION

During the past 5 years, the Bitterroot Resource Conservation and Development Committee (RC&D), the Intermountain Forest and Range Experiment Station, the Forest Service, and the Bitterroot National Forest have worked together to identify and evaluate alternatives for expanding forest-based industry in the Bitterroot Valley. The level of unemployment and underemployment is high among Bitterroot Valley workers who depend, at least in part, upon woods work for a living. At the same time, substantial volumes of available wood are not being utilized: extensive dead timber, smaller stems in stagnated stands, and material left on the site as residue following conventional logging operations (fig. 1). These conditions typify mature lodgepole pine stands, which until recently have been only lightly utilized for timber products.

Figure 1.--Typical lodgepole pine stand.

In 1972, fieldwork was completed for the regular forest inventory of the Bitterro National Forest. This inventory provides estimates of areas of various forest types a land classes, timber volumes, growth and mortality, silvicultural needs, and related data needed for forest management planning. The following year, supplemental fieldwor was done by the Intermountain Station in mature lodgepole pine stands to provide more detailed inventories and information on the utilization potential, particularly for th dead, down, and small-size material that frequently remains as residue after logging.

This report summarizes the utilization potential of mature lodgepole pine stands, including this "residue material." Comprehensive data on the timber resource for othe forest types are contained in the various summaries and reports compiled by the Bitter- root National Forest and the Regional Office Timber Management Staffs.

AREA AND VOLUME OF MATURE LODGEPOLE PINE

The Montana portion of the Bitterroot National Forest outside of classified Wilde ness has a total area of 829,771 acres. Of this, 749,969 acres is productive forest land--land capable of growing at least 20 cubic feet per acre per year of wood fiber. A portion of this productive forest land base is not available for logging under prese land use plans. The status of National Forest Lands outside Wilderness areas is as follows:

	Acres
Reserved (Lost Horse Scenic Area)	5,225
Deferred (New Wilderness Study Areas)	28,861
Unregulated (Commercial use is not programed at this time)	184,685
Unproductive, nonforest, and water	79,802
Productive forest base (wood fiber production)	531,198
Total, land and water base	829,771

Lodgepole pine is the second most extensive forest type, accounting for about 19 percen of the area (table 1).

About 80,000 acres of lodgepole pine is mature sawtimber and pole-timber (table 2) About 32,000 acres of this mature lodgepole is in the standard or special forest land category available for timber management purposes, and will be programed for harvest.

The remaining mature stands--about 49,000 acres--are in the unregulated-forest category. This includes high unproductive areas, remote areas, and administrative area Occasional harvest may be permitted in a small portion of this component, but the land use plan does not include scheduled harvesting.

Table 1.--[illegible]

Forest type	Standard	Special	[illegible]	[illegible]	[illegible]
Douglas-fir	153,728	116,258	93,514	[illegible]	[illegible]
Lodgepole pine	54,590	10,151	1,416	67,649	133,806
Alpine fir/spruce	28,505	7,726	1,730	89,707	127,668
Ponderosa pine	11,129	43,852	[illegible]	[illegible]	[illegible]
Other	--	--	[illegible]	7,651	7,651
Total	247,952	177,987	105,259	184,685	[illegible]

[1]Standard: Available and suitable for timber production with present technology.
Special: Needs special timber production measures to protect other multiple use values.
Marginal: Areas not presently scheduled for harvest because of excessive develop[illegible] costs, low product values, or resource protection constraints.
Unregulated: Commercial timberland not organized for timber production, including administrative sites, recreation areas, high areas, unproductive and remote areas, etc. Some harvest may be permitted but not on a regular scheduled basis.

Table 2.--*Area of lodgepole pine type by forest land class and condition*

Condition class	Forest land class: Standard	Special	Marginal	Unregulated	[illegible]
			Acres		
Mature, high-risk stand	3,221	1,[illegible]	[illegible]	16,848	[illegible]
Mature, low-risk stand	27,303	230	[illegible]	27,257	[illegible]
Mature pole	-	--	[illegible]	5,263	[illegible]
Subtotal, mature	30,524	1,796	[illegible]	49,368	81
Immature and nonstocked	24,066	8,[illegible]	1,416	[illegible]	[illegible]
Total	54,590	10,151	[illegible]	67,649	[illegible]

[1]Acreage in this table and acreage in Bitterroot National Forest inventory printouts may be slightly different because some mature stands have been harvested since the inventory fieldwork, and some land has been reclassified.

The mature lodgepole pine on the Bitterroot is mostly quite old--in some cases more than 200 years old. Most of the lodgepole grows in fairly high, cold sites that get most of their moisture from spring snowmelt. Summer and autumn are often very dry. Under these conditions, lodgepole stands will remain more or less intact for more than 200 years unless fire occurs. However, mortality is fairly heavy, and there is a large accumulation of standing and down dead material. Growth of individual trees is negligible, and net growth of the stand is often zero or negative, due to mortality (fig. 2,

Figure 2.--Overmature lodgepole pine stands on the Bitterroot National Forest average about 4,100 ft^3 per acre of wood 3 inches and larger of standing and down material.

Forest habitat type is an important characteristic in evaluating management needs and productivity of the forest. The mature lodgepole pine stands included in this stu are primarily in the alpine fir habitat types. Several other individual habitat types are also represented, but because there were relatively few samples in each, data were combined by major habitat series. The habitat types and areas are as follows:

		Acres
Alpine fir/(series) (Menziesia and Clintonia phases)	Moderately high productivity	3,558
Alpine fir/beargrass	Moderate productivity	36,031
Alpine fir/(series) (Luzula/Luzula-beargrass phase, beargrass/whortleberry phase, and dwarf huckleberry)	Low productivity	25,197
Douglas-fir/(series) (pinegrass and beargrass)	Moderately high	16,902
		81,688

Planning and land classification is currently progressing on the Bitterroot, based on the data now available from the recent timber inventory. A timber management plan for the period up to 1982 is planned for completion in early 1977. Although minor changes in land classification may occur, it is projected that of the 133,517 acres of lodgepole, approximately 66,000 acres would be available for management and utilization, with another 17,700 acres in which salvage would be permitted.

A large share of the unregulated portion of the lodgepole area is not available for utilization because productivity is so low, utilization is so costly, and management return so uncertain and low, it is not now practical to include in the timber base; or because of unacceptable adverse impacts to other resource values that would be incurred by roading and development:

Total unregulated lodgepole pine	67,650
Sites so low in productivity no management can be justified	- 14,823
Areas not available in present planning periods; may or may not be in future	- 35,024
Areas now available for harvest primarily because there is now road access and some harvest has occurred. Future harvest will primarily be salvage of dead trees.	17,732*

*Estimated lodgepole pine proportion of a total 24,000 acres of unregulated land now available for some harvest.

Assuming that about 70 percent of these 17,732 acres are mature stands (based on table 2), the total mature lodgepole area available for harvest is:

Standard	30,524
Special	1,796
Marginal	-
Unregulated	11,827
	44,147

CHARACTERISTICS AND PRODUCT POTENTIAL

Utilization of mature lodgepole stands depends in part on the volume of sound woo that could be recovered. About two-thirds of the mature lodgepole stands have 4,600 f or more of sound wood per acre. Some lodgepole pine stands in the Douglas-fir series have over 10,000 ft^3/acre, primarily because there are a few very large Douglas-fir overstory trees mixed in with the mature lodgepole. At the other extreme, some stands have less than 2,000 ft^3/acre of sound wood. The area and volume class of sound wood 3 inches dia and over, including live and dead, standing and down, is:

Vol/acre (thousand ft^3)	*Area size (acres)*
<2.0	5,983
2.0 to 4.5	10,100
4.6 to 6.5	19,659
6.6 and over	8,595
All	44,147

The total volume of wood in mature lodgepole stands averages about 4,100 ft^3/acre (table 3). About half the volume is in standing green trees; about one-third is down material, and the remainder is standing dead trees.

Much of the down material has rot, but only about half of this is crumbly rotten. About half the wood with rot in it is solid enough that it could be handled in logging and would provide fiber for some uses.

Standing trees have very little rot in them, even when they have been dead for several decades as is common in the area. This is probably because wood-decaying fung do not thrive in the high-altitude, dry, cool climate where most of the lodgepole grow and are active primarily on material close to the ground.

Total volume and conditions of wood varies somewhat among habitat type, but there doesn't appear to be any particular pattern and are probably due to sampling error. Therefore, we have used the average from all habitat types in the remaining analysis.

Based on the condition of wood in table 3, about two-thirds of the total volume would be suited for solid-wood products such as poles, posts, houselogs, and so on. Another 20 percent is suited for fiber products. This includes pieces with sound defec (excessive taper, crook, splits, etc.) and also pieces that have rot but are solid enough to be handled and used for pulp, fuel, particleboard, etc.

Size of pieces is an important factor in utilizing lodgepole pine, since handling many small pieces usually increases handling costs all through the harvest and process ing procedures. Most of the volume is in trees 8- to 12-inch diameter (table 4). Standing trees have over one-fourth volume in trees 12 inches d.b.h. and larger; down material has very little volume in 12-inch or larger pieces.

Table 3.--*Volume and condition of wood per acre in mature lodgepole pine stands*

Type wood	Suited for solid wood products	Suited for fiber products	
Down			
Crumbly rot			
Solid rot		478	
Sound defect		[illegible]	
No defect	235		
Standing			
Green			
Lodgepole	1,533		
Other	535		
Dead			
Sound defect		[illegible]	
No defect	471		471
Total	2,774	[illegible]	[illegible]

Table 4.--*Percent volume by diameter class of usable wood*

Diameter class	Standing live	Standing dead[1]	[illegible]	[illegible]
	Percent of cubic volume			
6 inches or less	[illegible]	[illegible]	[illegible]	[illegible]
8 inches	17	[illegible]	[illegible]	54
10 inches	27	21	[illegible]	20
12 inches	21	[illegible]	[illegible]	[illegible]
Over 12 inches	27	[illegible]	[illegible]	5
	100	[illegible]	100	[illegible]

[1]D.b.h. on standing, live and dead.
[2]Large end diameter on sound down pieces.
[3]Average diameter of piece on rotten down pieces.

Figure 3.--Field crew evaluating product potential. Much of the standing green timber and larger down dead pieces are suited for houselogs or saw logs. Smaller pieces lik the one in the foreground are suited for rails, posts, or fiber products.

To further define utilization potential, the types of products that could be made (fig. 3) from lodgepole pine were estimated. This evaluation was mostly quick, visual appraisal, but should provide a reasonable estimate product potential. On the down material, species was not always identifiable, so the summary includes all stems. For the standing trees, only lodgepole pine is included because we assume that alpine fir, spruce, and so on would not be used for roundwood products. In evaluating the trees, field crews were instructed to estimate potential roundwood products, first houselogs, then corral rails, and last, fenceposts. Specifications (minimums) were as follows:

Houselogs.--9-inch diameter, 8-foot length, with no crook, sweep, rot, or checks that preclude use as houselog.

Corral rails.--3-inch diameter, 10-foot length, reasonably straight, no rot or major checks.

Fenceposts.--3-inch diameter, 7-foot length, no crook, rot, or major checks.

The houselog, corral rail, and fencepost products are not necessarily optimum utilization, but rather are representative of an array of size and quality specifications, and provide a visual image of product potential in the stand. These evaluations were made independent of sawlogs; most houselogs, some poles, and some posts would also be suited for stud logs.

The number of product pieces are summarized below:

Type wood	Houselogs	Corral rails	Fenceposts
	(pieces per acre)		
Live	31	135	289
Standing dead	7	31	25
Sound down	10	26	27
All	48	192	341

Although this would probably be a maximum-value recovery, some houselogs, poles, and posts could alternatively be used for saw logs or stud logs.

The total amount of such products available from the Bitterroot depends on various land management and harvest activities, which are discussed later. Based on estimates now available, the approximate potential output per year is as follows:

	Annual production
Houselogs	15,000 to 27,000 pieces
Corral rails	62,000 to 100,000 pieces
Fenceposts	110,000 to 145,000 pieces
Fiber	264 to 555 M ft^3

CURRENT HARVEST OF LODGEPOLE

During the past few years, utilization of lodgepole pine has grown dramatically in the Bitterroot. Several houselog plants have been established, along with several post plants. Existing post plants have expanded and sawmill operations have increased their use of smaller size lodgepole.

In the past 10 years the harvest of lodgepole pine rose from about 3 million bd. ft. in 1966 and 1967 to over 9 million bd. ft. in 1971. During the last few years use has been about 4 to 6 million bd. ft. The volume of older, dead material has increased severalfold:

Year	Green	Older dead
	(thousand bd. ft.)	
1966	2,600	300
1967	2,600	500
1968	3,500	700
1969	5,700	370
1970	6,400	130
1971	8,100	1,525
1972	7,300	670
1973	5,100	1,000
1974	2,200	1,900
1975		3,000

In addition to wood harvested for products, firewood permits average about 1 million bd.ft. per year, principally lodgepole pine. Total harvest is between 5 and 8 million bd.ft. or about 2 million ft^3 per year.

POTENTIAL FOR UTILIZING MATURE LODGEPOLE PINE

This analysis of the lodgepole pine resource was undertaken to determine the potential for increased utilization of mature and overmature stands, particularly dead material currently left as residue that would provide additional wood fiber and increase the local economy and employment.

There appears to be some potential for increased use, but realizing this potential depends on location, economic conditions, technology, and feasibility for harvest, and on land management plans.

Location

Key factors in the potential use of the lodgepole pine resource are its location and availability. In our analysis of the resource, we did not attempt to make any detailed logging or roading appraisal. However, the small-scale map (fig. 4) shows generally where most of the lodgepole stands lie relative to existing roads. A larger (½ inch = 1 mile) map that shows individual stands of mature lodgepole in more detail is available from the Supervisor's Office, Bitterroot National Forest, or the Intermountain Station's Forestry Sciences Laboratory, Missoula, Montana. A highly detailed (2 inches = 1 mile) map of timber types is available at the Bitterroot National Forest. This map is about 15 years old but is accurate enough for general planning.

The general map (fig. 4) shows that most of the mature lodgepole stands are located along the high divides, somewhat remote from roads and towns. A large portion is in the West Fork Bitterroot drainage and the high elevations between the West Fork and East Fork. There is also a strip along the crest of the Sapphire Mountain Range on the east side of the valley. Most of the lodgepole on the west side of the valley lies within the Selway-Bitterroot Wilderness (this portion not shaded on map).

Economic Feasibility

Because of the remoteness and the relatively low value inherent in at least some of the lodgepole stands, current efforts to sell these stands often appraise out "negative;" that is, after all the various harvest and manufacturing costs are deducted from market value, stumpage has a negative dollar value.

Although the real price of wood has risen constantly, it is not likely to go so high (at least on a sustained basis) as to give all the lodgepole stands a positive dollar value under normal appraisal procedures.

However, there are probably several ways in which these costs can be partially offset, such as road financing in total or in part from sources other than stumpage value on a particular sale; attributing some of the timber harvest cost to restoring

Figure 1.--Index map of [illegible]

land productivity; reducing fire or insect hazard; improving esthetics or wildlife habitat; or similar benefits that can result from properly conducted harvests of decadent stands.

For example, a recent study of lodgepole harvesting in Wyoming showed that removing and field chipping "residue" (nonsaw log) material from the site cost about $262/acre more than conventional saw log removal followed by piling and burning. However, if today's chip prices or roundwood product prices were applied to that residue material the dollar values would probably be nearly equal. In addition the need for slash treatment was eliminated by near complete utilization, some esthetic gains were realized, and more wood was utilized from the site.[1]

Logging Systems

During recent years, the output of lodgepole pine products has increased substantially in the Bitterroot. Post and pole plants have enjoyed good markets, and a boom in log homes has created several new operations. One sawmill has installed a mill capable of handling material down to 2½-inch scaling diameter. In most of these operations, either lodgepole pine stands were cut selectively (that is, only specific products were removed), or lodgepole was taken as a component of a sale with larger volumes of other species and bigger logs. A complete removal of all material has not been the normal operating procedure.

We have studied one logging operation in cooperation with the Darby Ranger District and several logging operators, in which all or most of the lodgepole pine was removed in an overmature, pure lodgepole stand. The stand was logged for saw logs, posts, and poles. Pieces with rot were not removed, but sound dead material was taken. Briefly, the study showed that three different skidding methods--small, rubber-tired skidder; small crawler tractor; and horses--were all technically able to handle this type logging job. These methods were used because they are within the means of a part-time, small-crew logging operator. Productivity and amount of material removed varied among the methods, but all appear to have economic potential for operating in lodgepole pine. (A full report of the study is currently being prepared: John R. Host, Production and utilization in small stem lodgepole pine stands, Intermountain Station, Forestry Sciences Laboratory, Missoula, Montana.)

The more productive operations were the rubber-tired skidder and track skidder, averaging about 460 ft^3 of wood per man-day. Probably this could be improved to average 500 ft^3 per man-day or more. A portion of the mature lodgepole--probably 15,000 acres (mostly unregulated)--could be logged with such systems. The remainder would probably require skidding systems that keep logs off the ground (skyline or helicopter).

Alternative Marketing Schemes

Utilization of mature lodgepole pine stands throughout the Mountain States has been handicapped in the past because often the timber purchaser was interested only in the prime material such as saw logs and would leave smaller material in the woods. In addition, markets for most older dead and down material were lacking or erratic. One solution that has been proposed is to establish a marketing operation that would simplify the purchase of small log and "residue" material and provide a more stable means for both workers (loggers) and wood users to utilize the resource.

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[1]Benson, Robert E. 1974. Lodgepole pine logging residues: management alternatives. USDA For. Serv. Res. Pap. INT-160, 28 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

A feasibility study[2] was recently completed that considered several alternative operations for the Bitterroot. The simplest operation analyzed was a log marketing operation. Here the operator would arrange the purchase, harvest, and delivery of material to best utilize the available wood to meet the needs of wood users and provide work for loggers. He would maintain detailed and up-to-date information on location, availability, and logging requirements of small timber available from public land sale programs and private land sources. He would know specific needs of wood users and capability of operators, and would take care of much of the paperwork involved in public timber purchase. He would not take title to the wood (the sale contract would be between stumpage seller and either logger or wood user) but would collect $1/M bd.ft. (or the equivalent for roundwood or fiber products) for his service. About 33 million bd. ft. per year (roughly equal to 8 to 10 million ft^3 of small logs) would be needed to support this type operation.

Another type operation would be a concentration yard, where logs were sorted and stored. The operator could also provide much of the marketing services of arranging stumpage purchase and sales of logs to processors. Again, the operator would not own the logs, but would charge for the marketing, sorting, and storage service. If a $1/ton fee were used (a common basis for charging storage and handling operations) about 11 million ft^3/year would be needed to support the operation.

The most complete type of operation analyzed, a processing yard, would require only about 1 million ft^3/year, for feasible operation. (Of course a larger volume operation could also be established.) This would involve purchasing, sorting, and preprocessing (such as cutting to length, or chipping, etc.) for sale to the next processor or final user.

The actual feasibility of such operations of course depends on the economics of harvest, the availability of capital, participation by potential operators, and market conditions for final products. Furthermore, type and condition of wood available is such that the output could range from a fiber to a fairly large array of high-value roundwood or saw log products. The advantage of a marketing operation is that it could direct wood into active markets and take over the task of finding outlets for the wide range of products that occur in the mature stands.

Timber Harvest Schedules

Before utilization of mature and overmature lodgepole pine can be improved, the rate at which these stands might be harvested must be calculated. Obviously, rapid liquidation would minimize further mortality and loss to decay, and maximize the volume of wood available for immediate use. Such a plan, however, would have unacceptable impacts on other resource values, would ultimately lead to a decline in harvest after the rapid liquidation, and would require enormous initial road expenses. At the other extreme, if little harvesting is done in these stands, greater mortality, and ultimate loss of wood to decay or fire will result. Typically, the Forestwide harvesting schedule will remove high-risk stands first, then move into mature, low-risk stands. Protecting other resource values must also be weighed along with silvicultural needs and, even in the standard component, will temper frequency of cutting, size of harvest cuts, and types of harvest system. Generally, the mature lodgepole pine stands occur in relatively large-sized blocks (fig. 4). Due to the large amounts of down material,

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[2]Adair, Kent T. 1975. Stepwise development of a merchandizing-concentration yard. Outline and screening analysis, Bitterroot RC&D, School For., Univ. Missouri. Columbia. (Unpublished report on file at Intermountain Station's Forestry Sciences Laboratory, Missoula, Montana.)

harvest systems employed will usually be clearcutting or two-stage shelterwood cuts. Both systems require total removal of all stems on the area treated; clearcutting in one operation and shelterwood in two. Clearcutting will be involved on approximately two-thirds of the acreage in the standard component, with shelterwood for the remainder and shelterwood or group selection for the special component.

Preventing overconcentration of harvesting activities or large size of cutting units in any one area will generally be the primary constraint on rapidity of harvest. As stated previously, the majority of lodgepole pine stands are on the high divides at elevations exceeding 6,000 feet. Most are in the alpine fir/beargrass habitat type where recovery periods following disturbance range from 20 to 25 years. This means that high impact cuts will require a 20- to 25-year recovery period before similar cuts can occur in stands immediately adjacent thereto. Generally speaking, 1 acre in every 4 or 5 can be in a high impact cut in any 20-year period. Therefore, it will require from 80 to 100 years before the existing, mature high- and low-risk stands will be totally removed, and up to 120 years for shelterwood and group selection cuts. Most of the volume would be removed within a 100-year period.

Based on the above, and considering all usable green and dead products, average annual harvest would amount to 323 acres or about 900,000 ft^3 of solid products and 300,000 ft^3 of fiber (table 5). An assumption made here is that growth will be balanced by decay and that usable fiber per acre will remain essentially unchanged over the 100-year period.

Removal of dead material might possibly be accelerated on the 10,000 acres where tracked or rubber-tired skidders could be used. Usable dead material amounts to 1,525 ft^3 per acre. If access and markets are favorable, this material could be removed in about 20 years and perhaps sooner. This would mean an additional 500 acres per year (removal of dead volume only) or up to 400,000 ft^3 of solid products and 400,000 ft^3 of fiber. In addition, salvage could occur in that portion of the unregulated component that has already been roaded. Approximately 3,500 acres are suitable for the use of rubber-tired skidders. Again, using a 20-year period, about 175 acres could be harvested annually (removal of dead and recent mortality) or up to 160,000 ft^3 of solid products and 140,000 ft^3 of fiber (table 4).

In total about 2.2 million ft^3 would be removed annually (fig. 5) over a 20-year period. About 29 percent would be green material, the remainder dead; unless already roaded, access for removal of dead volume only would have to be provided from appropriated funds. High markets would probably be required to make most sales economically feasible. Thus, removals will probably not occur on a smooth annual basis but periodically during good markets and as appropriated funding becomes available for road construction. More detailed estimates of harvest scheduling and economic feasibility will be provided in the Forest's new Timber Management Plan scheduled for completion in 1977.

A. [illegible] - Harvest of all [illegible]
(standard land)

Condition	[illegible]	[illegible]	Fenceposts	[illegible]
Live	10,013	15,605		
Standing dead	2,261	10,015	8,075	12.9
Sound down	[illegible]	[illegible]	8,221	221.6
[illegible]	[illegible]	62,016	109,645	

B. Additional [illegible]ties - Accelerated [illegible]
[illegible] round-[illegible]id and unregulated land)

Condition	[illegible]	Corral rails	Fenceposts	[illegible]
Live				
Standing dead	4,725	[illegible]	16,875	
Sound down	6,750	17,550	18,225	165.0
Total	11,475	38,475	35,100	552.8

C. Total - sum of most probable and additional possibilities

Condition	[illegible]	Corral rails	Fenceposts	[illegible]
Live	10,013	[illegible]	93,347	
Standing dead	6,986	30,958	21,950	
Sound down	9,980	25,948	26,936	681.6
Total	26,979	100,491	145,245	817.3

[illegible]
Corral rails, minimum - 3-inch diameter, 10-foot length
Fenceposts, minimum - 3-inch diameter, 7-foot length.

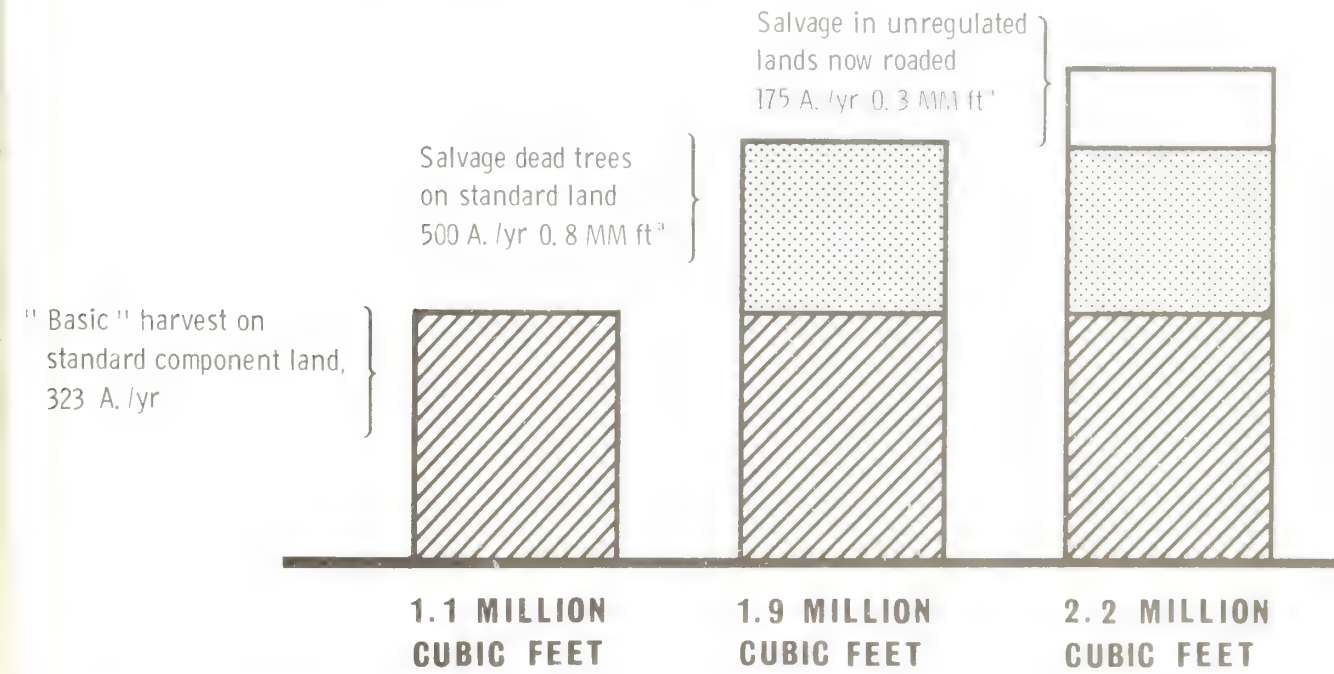
Salvage in unregulated lands now roaded 175 A. /yr 0.3 MM ft³
Salvage dead trees on standard land 500 A. /yr 0.8 MM ft³
" Basic " harvest on standard component land, 323 A. /yr
1.1 MILLION CUBIC FEET
1.9 MILLION CUBIC FEET
2.2 MILLION CUBIC FEET

Figure 5.--Alternative [illegible] National Forest.

CONCLUSIONS

A considerable wood volume--over 180 million ft^3--in mature lodgepole pine stands on the Bitterroot National Forest is not being fully utilized, but is available for harvest. Two-thirds of this wood is suited for fairly high value, solid wood products and another 20 percent is suited for fiber.

The key factors in utilizing this wood are the annual volumes available under the forest harvesting schedule, accessibility and roading, and market conditions and wood prices.

Under current guidelines for protecting watershed, about 1.2 million ft^3 per year could potentially be harvested on standard and special land. This volume could be produced by clearcutting about 323 acres per year.

Another 0.8 million ft^3 of salvageable dead material could potentially be harvested from standard and special lands. This partial cutting (on about 500 acres per year) would capture values in dead trees that might be lost by the time a final regeneration cut is made. About 0.3 million ft^3 more of dead material could be salvaged from unregulated areas that already have road access.

Most of the potential lodgepole will require roading to provide accessibility and harvest. Because of the low values in much of the overmature stands, it is not likely that these stands can support full road development costs.

There may be some opportunity for the lodgepole pine resource to provide part-time, labor-intensive employment for local residents. Thus, opportunity could be enhanced if a convenient and dependable market outlet for logs is available. Several alternative types of market outlet, such as concentration yards, appear to be economically feasible if the potential annual harvest from overmature lodgepole stands can be made available.

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three-fourths of the total volume of these stands is suited for high

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Bitterroot National Forest. USDA For. Serv. Res. Pap.

stands in the Bitterroot National Forest, Montana, are presented. Growth is low and deadwood volumes are high in these stands, but three-fourths of the total volume of these stands is suited for high value products such as houselogs, posts, and poles. Up to 2.3 million cubic feet per year could be harvested.

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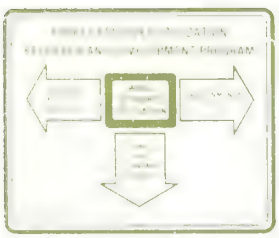

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